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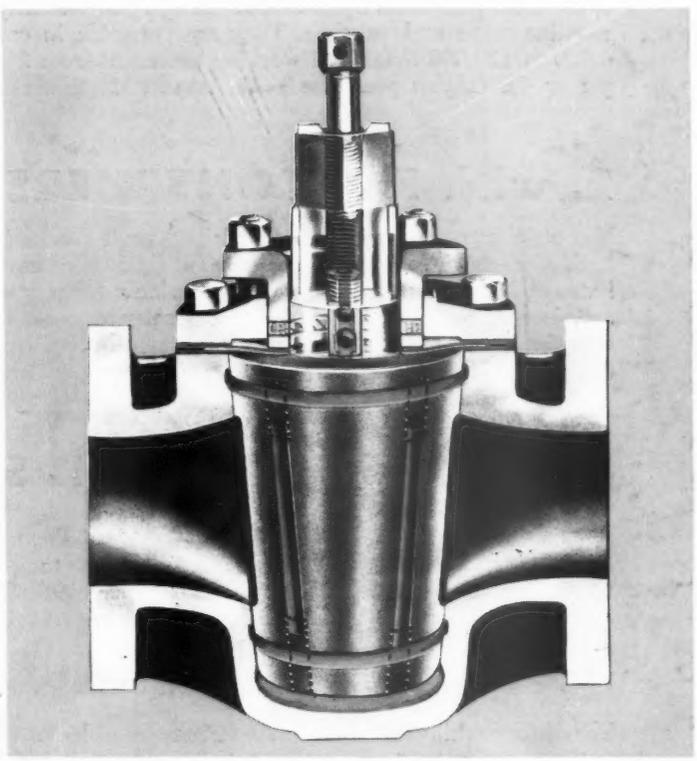

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Editorial

This Reference Annual of *The Petroleum Engineer* contains some of the top papers of the year, selected from the various divisions of the petroleum industry. Every reader will find articles of value and importance in his field.

The second issue of the bibliography of papers that were given during the preceding year has outgrown the Reference Annual. We accept our responsibility, however, for continuing this valuable aid to research and thence to progress.

During the coming months the 1948-49 bibliography will be published as part of the Continuous Tables. The bibliography will be indexed by author, subject, and society before which paper was presented, and will provide an up-to-date reference to current trends. As is done for the reader in the general "Readers' Reference Guide" and the more specific "Industrial Arts Index" and "The Engineering Index, Inc.," we shall endeavor to keep up with the latest published reports — in this case limited to the petroleum industry.

Most of these papers will be available from the societies or the magazines in which they appear and can be obtained from the publishers. The bibliography will include information about where copies can be procured.

The decision to publish the bibliography in other issues has meant the publication of a larger and more comprehensive number of outstanding papers in the 1949 Reference Annual. We present it in the hope and belief that each reader will find herein a new idea, a better method, a brighter outlook.

The Petroleum Engineer

P 900.

REFERENCE ANNUAL 1949

THREE P'S IN A POD

Prices, Profits, Productivity in Petroleum†

ROBERT G. DUNLOP*

It is with a sense of privilege and high honor that I appear before you in response to the invitation of President Boyd to discuss several of the fundamental economic factors underlying that state of the oil business today.

Among you are many with far more years of experience in the petroleum industry than I have enjoyed. All of you fully understand and practice the basic principles of a free-market, competitive enterprise economy. Lest anyone suspect me of carrying oil to East Texas, let me assure you that my mission is not the conversion of unbelievers, but rather an exhortation to the faithful to raise the banner of a free, competitive industry, and disseminate the truth.

Never in recent years, at least, has there been more widespread ignorance and misunderstanding of the function of prices and profits as stimulators of productivity under our competitive enterprise economy, than exists today. In view of the steady stream of collectivist propaganda to which the American people have been subjected since the war's end, it is not surprising that this should be so.

But unless this ignorance and misunderstanding can be cleared away, our competitive enterprise system is in serious jeopardy of being disrupted by ill-conceived governmental restrictions. Consequently this subject merits the attention and concern of each of us.

We must correct the widespread popular belief that profits are just a residue paid out to stockholders when a company's books are closed. We must make it clear to all our people that profits have definite jobs to do that are vital to the operation of our competitive economy. And let there be no misunderstanding. Our interest in a competitive economy is not as an end in itself, but as a means to an end —the end being an improved standard of living for the American people.

First, profits constitute the wages or rental that a company pays for the plant and tools supplied by stockholders—the plant and tools on which productivity is based and which are the very foundation of well-paying jobs.

But, as you well know, profits in a competitive enterprise economy perform many other functions. They are the gauges in our general office control rooms which signal the economic temperatures and pressures of the times.

For example, profits, when they become large, signal the need for expansion in those lines of production in which demand is increasing. Contrariwise, a lack of profits indicates the necessity of contraction in those industries which have been over-expanded or whose products are in diminishing demand.

Not only do profits signal the need for expansion, but profits induce people to risk their savings in those enterprises which will produce goods and services that the rest of us want and are able to buy.

Profits serve as the most important method of accumulating funds which are needed for new capital investment. This is true whether the profits are reinvested in the business or paid out to stockholders. In either instance, they are the means for capital formation which is essential to all industrial expansion.

Once an investment has been made, the margin of profit serves as a recorder or yardstick of the efficiency of the managers of the enterprise, unless the latter enjoys some kind of monopoly position. Thus to maintain reasonable profits in a competitive industry, the managers must be alert to improved quality and services, increased volumes of sales and prices as low as those of their rivals.

Adequate profits are essential for business and industry to fulfill their responsibilities to serve the general welfare. They stimulate expansion and competition, thus providing more and better goods with consequent lower prices. They give people an incentive to invest their savings. And they act as a guide and a regulator of the flow of capital funds.

As long as profits are permitted to perform these functions, our economy will remain dynamic and strong, serving the needs of the American people.

The heart of the profit system is the price mechanism which in a free market adjusts the supply and demand for goods and services. This adjustment is made (in other words, prices are determined) in the market place through the free and competitive bidding of many buyers and many sellers. Short-run market prices result from the interplay of supply and demand factors, regardless of the cost of producing a

*President, Sun Oil Company, Philadelphia, Pennsylvania.

†Presented before the General Session of the 28th Annual Meeting of the API, Chicago, Illinois, November 11, 1948.

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given commodity or of the profits which may result from selling it. A too little-appreciated fact is that customers, through the pressure of their demand, determine prices in a competitive economy.

Of course, in the long run—say, over a period of several years—if the market price for a commodity has not been sufficiently high to cover costs of production and to yield a return on investment for all producers, the less efficient firms producing that commodity will be forced out of business or they will abandon production of that particular commodity. As a result, fewer units will be produced, the market price will rise because of insufficient supply, and profit margins will be restored.

On the other hand, when market price for a commodity is high enough to yield an exceptionally good profit, existing firms start expanding, and, perhaps new firms are started. The supply is thus increased. Competition thereupon grows sharper and prices fall when the supply reaches a point slightly in excess of the demand at the existing price level. This results from the competition of sellers in disposing of their production.

Such are the traditional operations of the laws of supply and demand in our competitive enterprise economy. Nor is the effect of these laws nullified by the inflationary forces that have been at work in this country for several years. Generally speaking, inflation has given increased force to the demand side, without, however, having brought about a corresponding balance in supply.

This condition results from a sharply increased supply of money which is a direct consequence of loose monetary policies and federal government deficit financing, aggravated by huge war spending. Thus there has taken place a national accumulation of much more money than there are goods and services to buy with it at existing price levels.

We have today, including both money in circulation and deposits in comercial and savings banks, two and one-half times as much money as in 1939. But since 1939, despite record-breaking industrial achievement, the production of goods has increased only 78 per cent. Thus over the last eight years the money supply has increased about twice as fast as the physical output of our mines, factories, shops and farms.

The inevitable result has been a greatly increased demand for most commodities that could not be met by supplies, with sharply increasing prices bid up by those with the money to do so. While increased production is helpful, only a correction of the unsound monetary policies of the past and an end to deficit financing by the government can bring these inflationary forces under control.

And that, too, gentlemen, is a story that needs to be told far and wide. Business and industry cannot hope to achieve public understanding and acceptance of their current operations as long as people generally mistake the manifestations and results of inflation for its cause. The cause of this inflation is precisely the injection of increased quantities of money into circulation by a process which has been but one stop short of an outright printing press operation.

Everything else—round after round of increased prices and increased wages and credit expansion—are but consequences of the increase in the quantity of money that resulted from the monetizing of the government debt. Thus the pre-war value of the American dollar has been cut approximately in one-half. When that fact is understood generally, we shall be on our way to solving our chief difficulties. Let us not deceive ourselves, we shall not get on solid ground until that fact is fully recognized by our people and government has the courage to correct the fallacious policies of the last 18 years.

Turning now to the oil business, we witness an outstanding example of competitive enterprise and the specific application of these fundamental economic laws which we have just reviewed in their general operation.

In our industry events of the last three years demonstrate beyond all possibility of dispute that prices, profits, and productivity are interdependent. I have likened them to "three peas in a pod"—and so they are. Like the peas in a pod, each is separate in itself; but each also is joined to the other. Factors affecting any one of them, influence the others. The pod, of course, is our competitive enterprise system.

Much has been said about oil's sharply increased profits. Not enough has been said about the tremendous job that oil men and women have done in stepping up production to meet the postwar demand.

It is superficial and meaningless to say that 1947 oil industry dollar profits were approximately 60 per cent greater than in 1946 and that this year's net earnings are running at substantially higher levels.

Such dollar earnings are the greatest in the history of the oil industry. But whether it is evidence of a healthy economic situation remains to be seen in view of the attendant circumstances. For to be properly appraised, these earnings must be related not only to the general economic situation, but also to the general oil supply-demand picture, to the volume of sales, to prices, to the purchasing power of the dollar, and finally but most importantly, to the obligations (involving replacement and expansion problems) resting on the industry to supply the oil needs of the consuming public. Only as this is done can current oil profits be made meaningful and significant.

Increased sales volume, requiring, for the most part, capacity operations and increased prices have contributed to the oil industry's profit picture. It should be emphasized that both, in large part, grow out of the inflationary situation created by increased supplies of money and price disparity caused by government controls.

The elements of the increased demand for petroleum products needs no demonstration before this gathering. However, factors underlying the price increase need to be repeated because they are too often forgotten.

Foremost is the fact that wartime price controls for all practical purposes froze oil prices. You know the refusal of O.P.A. to permit any increase in the price of crude oil, despite rising costs resulting from inflationary pressures. Product prices were permitted only to rise slightly. For instance, whereas in the 1941-45 period, coal prices were permitted to rise approximately 27 per cent, prices for petroleum and its products were allowed to advance only 12 per cent.

Importantly, the disparity thus created was responsible in part for the postwar rush to install oil burners and to convert to oil industrial plants burning coal.

When OPA controls ended, petroleum and its products were selling at wholesale for one-third less than their 1926 average prices but all commodities making up the index were selling on an average of 13 per cent above the 1926 base. In the face of this situation and the intensive postwar demand, oil prices began to rise in 1946 and the corrective adjustments which were so badly needed have since been taking place.

Since 1946 the general level of crude oil prices has been raised five times (one authorized by OPA) for a total of $1.40. None of these increases (except that granted by OPA) directly resulted from the fact that someone merely thought a price rise would be a good idea and then acted. In each instance there was a very real and aggressive demand pressure by someone needing oil that forced the price up. In each instance it reflected a tight industrywide supply-demand situa-

The Reference Annual is a special number, not one of the monthly issues, and therefore does not carry the regular features. The contents are selected papers of significance that have been presented during the previous year.

tion. If that were not true, the increased price would not have held.

The situation leading up to these price increases was one of demand gradually overwhelming supply. The obvious public desire was for larger supplies of oil products, which, of course, required increasing supplies of crude oil. Both proved economic concept and the history of oil production indicated that this requirement could not be achieved by a stationary price, irrespective of whether such action came as a result of governmental edict or industry predilection.

Historically the trend of well drilling follows the pattern of crude prices, as I shall subsequently demonstrate. New oil discoveries as well as increased production are dependent on well drilling. Thus, even though demand dictated the price increases, it was believed that they would prove to be incentives for stimulating increased production.

This precisely has happened. Since the first 1947 price increase, March a year ago, domestic oil production has increased from a daily average of 4,784,000 bbl to a new high of 5,604,000 for the week ending October 30 this year, the latest figure available. This latter figure was 820,000 bbl of daily average production over March 1947—an increase of 17 per cent. Preliminary to that production was the fact that well drilling last year was 13 per cent greater than 1946, and this year it is estimated the additional wells completed will show an even larger increase.

Actually the oil industry has become a leader of industrial expansion. The Federal Reserve Board reports that since 1941 crude oil production has increased 46 per cent. But in that period iron and steel output increased only 11 per cent; lumber and its products 17 per cent; automobiles 31 per cent; bituminous coal 22 per cent, and all manufacturing production 19 per cent.

Obviously, therefore, increased prices have had the effect of increasing supplies of oil and this is what the consuming public has desired. But has the public, as a few critics have suggested, been forced to pay "through the nose" to get these increased supplies? The answer is to be found in a frank comparison of oil prices with prices for other commodities and the general price pattern of the nation.

Altogether since the war's end, generally posted crude oil prices have advanced $1.40 a barrel, or, on the basis of East Texas crude, 112 per cent. Actually this represents the increase in crude oil prices since 1941 because the OPA froze crude oil prices at the level of the end of that year.

Admittedly this increase constitutes a sharp rise in price, but actually it is less than the depreciation of the purchasing power of the dollar, which has taken place as evidenced by greater price increases for many other commodities. For instance, in the period 1941 to this fall wholesale raw material prices on an average increased 116.2 per cent and the average increase of wholesale prices for farm products increased 130 per cent.

Increase in crude oil prices have been reflected only in part in increased prices to consumers for gasoline, heating oils, and other petroleum products. At service stations across the nation motorists today are paying an average of only 35 per cent more, including tax, for gasoline than they did in 1941. Meanwhile the Government's Consumers' Price Index (covering such things as clothing, groceries and furniture), in the same period rose 66 per cent.

Wholesale and retail prices of kerosine, furnace oils, and heavy fuel oil have risen more precipitously than have gasoline prices. Demand for these heating oils has sharply risen, out-running their supply. As previously pointed out, however, demand in excess of supply is the factor responsible for price increases.

We all recall that prior to recent postwar price readjustments, fuel oils in varying degree sold at prices less than their value for conversion into gasoline. Efficient refinery operations, under such circumstances, generally require that the maximum amount technically possible of a barrel of crude oil should be processed into gasoline as long as there is a market for such gasoline. Recent increases in fuel oil prices have eliminated this disparity and therefore have provided incentives for refiners to produce these products. Likewise these increases have closed the gap between oil and coal prices created by OPA action.

Certainly oil as yet has not commenced to price itself out of customers, as coal has been doing for years. Although the rate of increased demand for furnace oils this year, as estimated, is not as great as it was last year, the increment is higher than normal.

Even to keep up with a normal annual increase in demand, taking into account the increases in demand for motor fuels, the oil industry not only has been required to keep up its existing facilities but to pursue an expansion program far greater than any undertaken in the past. Therein is the crux of the industry's problems.

The replacement of existing plant and the expansion of facilities must be made at costs which today are greater than twice pre-war construction and equipment costs. This constitutes a serious problem for all industry, but it is extremely serious for petroleum where capital investment per employe and per dollar of annual sales is substantially greater than in other industries, as illustrated by comparison with steel, rubber, and automobiles.

Further, while current depreciation allowances recognized by the Bureau of Internal Revenue are sufficient to recover the original cost of plant construction, they are grossly inadequate to provide for its replacement at today's prices. Failure of industry to replace and keep modern and efficient its existing facilities means retrenchment, less production, fewer jobs, and a consequent inability to meet customer demand.

In order to keep existing plant and equipment up to present standards and to expand facilities to meet the increased demands for petroleum products, the industry in the last two years has made capital expenditures averaging $2 billion annually. Such expenditures are at a rate twice the average for the war period and approximately three times the average for the five years preceding the war.

Were it not for the fact that petroleum industry profits have been rising, the source of funds for the replacement and expansion reflected by this huge capital expenditure would create a critical problem. But the forces of demand, which have resulted in higher prices and a need for increased facilities, at the same time have generated greater dollar net earnings available for use for replacement and expansion of plant to fulfill that demand.

Owners of the oil industry—the stockholders—to whom profits rightfully belong, have permitted their companies to reinvest a major portion of their profit-money to provide facilities for meeting the demand and thus, in time, lowering prices, and the ratio of profits to the sales dollar.

Joseph E. Pogue and Frederick G. Coqueron of the Chase National Bank, in their Thirty Company Study computed that last year stockholders of

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these companies took only slightly more than one-third of the profits, leaving virtually two-thirds for reinvestment in their respective enterprises.

Consequently, the cost of replacements in excess of depreciation allowances and of plant expansion is provided for by the stockholders through foregoing a dividend return that rightfully belongs to them. In other words, the stockholders are willing to reinvest a large portion of a company's earnings in the hope of future profits through increased volume, and to safeguard their original investment through maintaining the dynamic structure of the enterprise.

While capital funds may be secured in various ways, capital itself cannot be created except through savings, that is, expending less than is produced or earned. It is a fundamental concept that corporate enterprise to survive in the long run must create, as a result of its operations, the capital necessary to effect its reproduction. Therefore, the higher degree of internal creation of capital, the sounder the industry is generally, and the greater its stabilizing influence on the entire economy. Traditionally, the oil industry has generated most of the capital needed for its expansion over the years.

Entirely aside from the historic practice of the industry, current rates of taxation and credit restrictions place limitations on the availability of outside financing.

But irrespective of whether funds come from within or from outside the industry, a level of profits commensurate with the capital funds needed to meet demand is essential to obtain them. Loans must be repaid, and additional stock issues require additional earnings in order to maintain the value of the securities.

If the level of profits is not commensurate with the need to meet demand, then the expansion essential to meet that demand cannot take place. As long as the forces of supply and demand, operating in a free market place, are left unrestricted (except by the free choice of consumers), the industry can generate the means of meeting the demand of these consumers.

But this is not possible should artificial controls be imposed on the free market. Should the federal government sharply increase taxation of corporate profits, radically reducing their net income, then the means for expanding the oil industry would be hobbled and to the extent that this takes place, needed expansion would have to be deferred or abandoned. The result would be a continued tight supply-demand situation. Prices would go higher unless controlled by government.

Imposition of governmental price controls, however, would most certainly limit or reduce the output of high cost or marginal producers. In fact, it would, by destroying incentives, adversely affect all production. The mere threat of such action last winter caused deferment of many drilling programs, until the danger had passed.

Meanwhile, unless steps are taken toward limiting the national credit and money supply, demand for oil would remain as great and pressing as now. In the end the government would be forced to ration oil products, which in volume would grow less and less. The result would be that everyone concerned would be hurt, particularly the consumer.

As a matter of fact, oil industry profits in 1946 and 1947, were not out of line with pre-war net earnings when reduced to a per cent of the sales dollar. This is illustrated by the net earnings per dollar of sales of the Pogue-Coqueron Study of Thirty Companies from 1934 to last year. Peak earning years were 1937 with 11.9 cents; 1947 with 11.6 cents; and 1941 with 10.9 cents. Earnings statements this year indicate a somewhat higher ratio of return for 1948 but the specific data will not be available until the year ends. Of course, none can say how long such a ratio will be sustained.

And now, in conclusion, to those who would challenge our operations, let us make crystal clear these points:

1. An excess supply of money in proportion to production, resulting from loose monetary policies, is responsible for spiraling demand for most commodities and consequent inflationary prices.

2. This general economic condition is the basic cause for an unprecedented postwar demand for petroleum products, although increased population, desirability of products, and price disparities also have been factors.

3. Per capita consumption of oil products in the United States since 1941 has increased about 34 per cent, thus raising living standards.

4. This demand, outrunning the supply of petroleum products, has resulted in crude oil prices more than doubling since 1941, although product prices to consumers have not risen nearly as much.

5. Despite sharp increases, crude oil prices have lagged behind prices for other raw materials and retail petroleum product prices taken together, have lagged behind the Consumers' Price Index.

6. Increased prices for crude oil have greatly stimulated exploration and drilling, have stepped up supplies from secondary recovery sources, and have increased over-all production to peak levels.

7. The petroleum industry thus has been a leader of industrial expansion, having increased output substantially more than other major industries since 1941.

8. Increased prices and capacity sales volume together have more than doubled oil industry dollar profits since the end of the war, but last year only one-third of these profits was paid to stockholders.

9. Profits reinvested in the oil industry have made possible a $4,000,000,000 capital expenditures program for 1947-48—a rate twice that of the war years and almost three times that of the pre-war period. Without such profits this would not have been possible.

10. This program provides for the replacement of existing plants constructed and developed prior to the war at costs about one-half of what they are today, thus making it possible for the industry to maintain output.

11. Included also in this program is an expansion of facilities for increasing supplies needed to meet demand and to set in motion forces that make for increased competition and lower prices.

12. With this utilization of profits, the oil industry, can, and is satisfying the desire of the American people for oil products and a better standard of living.

This, I submit, is competitive enterprise in action. When told to the American people it will appeal to them for they believe in it as a system superior to all others.

Today we face the danger of having imposed on us a collectivist economy in the form of measures disguised as mere remedies for current and temporary ills. Beguiling voices are calling the American people to turn their backs on a free, competitive market place and put their faith in government controls that can lead only to the police state. If we yield to these siren voices, they shall lead us to the destruction of that individual opportunity and freedom of choice which is the foundation of our national well-being.

Let us, with all our hearts and strength, with facts and truth, before it is too late, point out to the American people that a competitive, progressive petroleum industry, operating in a free market place, will best serve their welfare by providing to the consuming public and to the Armed Services adequate supplies of petroleum products, at reasonable prices, now and in the years ahead. ★ ★ ★

Factors Used in the Allocation of Production Among Pools and Within Pools*

EDGAR KRAUS†

Abstract

Present practice in allocation of production among and within pools in the principal oil-producing states is reviewed briefly. Factors now used are compared to recommendations previously published by API committees. Although no detailed evaluation of factors is attempted, some general comments on the effect of such factors in allocation formulas, and on general trends, are included.

History

THE API Special Study Committee on allocation of production and well spacing and its predecessors have from time to time issued progress reports and have sponsored papers in which factors that might be used for the allocation of production were mentioned, suggested, and recommended. Other factors, after study, have been found unsuited for such use.

In 1933-34, under the title "Essential Engineering Factors in the Allocation of Production,"[1‡] a progress report was issued in which the following factors were reviewed: 1, Productivity; 2, Acreage; 3, Bottom-hole Pressure; and, 4, Sand Thickness. Some skeleton formulas having possible usefulness for allocation within pools were cited as illustrations, but no specific formula was recommended.

A progress report[2] dated 1938 mentioned what, under modern parlance, would be referred to as maximum efficient rate (MER) for the field as a whole. Ratable withdrawals and allocation so designed as to prevent drainage across property lines were recommended. This report condemned "per-well" potential as a factor in allocation.

In 1940 the committee discussed in a progress report[3] such factors as: 1, Reserves; 2, Market Demand; 3, Wells; and, 4, Depth, which might be used in determining allocations between states and fields within states.

In 1941[4] these same factors were again mentioned, with the addition of "MER" and the recognition that acreage in itself is some measure of reserves.

The latest published progress report, titled "Standards of Allocation of Oil Production Within Pools and Among Pools,"[5] was issued in 1942; and, in discussing allocation within pools, such factors as 1, Acreage; 2, Thickness; 3, Bottom-hole Pressure; 4, Potential; and, 5, Wells, were mentioned. The use of wells alone was condemned, unless specifically associated with a uniform well spacing. So, too, was "potential" as a factor questioned, although its use might be required by statutes in some states. For allocation among pools within any state such factors as mer, market demand, reserves, and depth were again mentioned, and recommendation made that such allocation be on some definite plan.

Summarizing, then, this committee has from time to time mentioned the following possible factors which might be used in a proration plan:

1. Productivity—in early reports; not now recommended.
2. Acreage.
3. Bottom-hole pressure.
4. Sand or pay thickness.
5. Reserves.
6. Market demand.
7. Depth.
8. Wells—rejected unless provision made for uniform well spacing.
9. Potential—rejected as unsound.
10. MER.

Of all these factors enumerated, present engineering thought would eliminate or greatly lessen the effect in allocation plans or formulas of productivity, wells, and potential.

It is interesting now to survey conditions in the various oil-producing states to learn to what extent these various factors are being used. Such use is a measure of the degree of acceptance by the states, and also by the industry, of the engineering principles involved. Although it is true that the various regulatory bodies and the legislatures of the states formulate the rules, laws, and legislation upon which the various proration plans are based, there is, nevertheless, an observable tendency for those bodies to reflect a majority opinion of the industry as a whole; and, certainly, when there is unanimity within the industry, then the legislation and regulations ultimately conform in large measure to such opinion.

The following review of proration and allocation practices in the principal producing states is based on information supplied by members of the API Special Study Committee on allocation of production and well spacing. It reflects overall practices in each state, and should not be considered statistically correct on any specific date.

REVIEW BY STATES

Arkansas

MER and market demand are the factors used in allocation among pools within the state. A study by B. J. Dowd* late in 1947 of 34 prorated fields showed six different combinations of factors, as shown in Table 1.

California

R. E. Loeck† and William R. Wardner, Jr.,‡ have summarized allocation practices in California.

Distribution between pools: Under a voluntary program, "the Conservation Committee of California Oil Pro-

TABLE 1.

Allocation method	Number of fields	Per cent
Wells	22	64.7
Acreage—bottom-hole pressure	5	14.7
Reserves (volumetric)	3	8.9
Acreage (with gas-oil ratio limitation of 3,500 to 1)	2	5.9
Wells—reserves	1	2.9
Acreage	1	2.9
	34	100

Except as noted, all field allowables are adjusted for gas-oil ratios in excess of 2,000 to 1.
23 fields use well allowable; 8, acreage; 4, reserves; and 1, bottom-hole pressure.

*Paper presented to a Division of Production Group Session during the 28th Annual Meeting of the American Petroleum Institute, in the Stevens Hotel, Chicago, Illinois, November 9, 1948.

†The Atlantic Refining Company, Dallas, Texas.

‡Figures refer to References at end of article.

*Union Producing Company, Shreveport, Louisiana.

†California Research Corporation, San Francisco, California.

‡Manager, Conservation Committee of California Oil Producers, Los Angeles, California.

ducers," elected by the operators, determines MER's monthly, which limits production in flush pools. The committee does not consider market demand or allocate production as such to pools.

Allocation within pools: A general formula and many special formulas include as factors: acreage, wells, thickness of pay, MER, pressure, and productivity index. Suitable correction factors are used for formation-volume factor, gas-oil ratio, and marginal or minimum credits in the determination of which depth is a factor. Most of the factors are used as multipliers rather than as additives, except that in many instances one-half of the pool's MER is divided on the basis of wells alone, and the other half on the basis of a formula.

In 1947, of 156 pools defined as having such characteristics that loss of ultimate yield will result from capacity production, 66 used a so-called "general formula." With it a minimum allotment is guaranteed to each well in the pool. The quantity increased with depth. The relative capacity, or maximum good operating rate, of each well is estimated and the remainder of the pool MER [i.e., MER less minimum allotments] is distributed to wells on the basis of the relative capacity (potential). In some cases a power factor less than one is applied to suppress large differences in relative capacity. The minimum allotment guaranteed is 1 bbl per day per 200 ft of depth to 1000 ft, then adding cumulatively 1 bbl per day for each 100 ft of additional depth—but no well to receive less than 10 bbl per day if capable of that production.

In 19 pools of this class which involve single-company or unit operations, only MER is assigned to the pool, and production distribution to the individual wells is left to the operator. Other pools use factors in the formulas shown in Table 2.

TABLE 2.

Factor	Number of pools
Wells	12
Acreage	16
Sand thickness	14
Bottom-hole pressure	17
Gas-oil ratio	10
Formation-volume factor	15
Productivity index	1
Water cut	2
Top well limits:	
Oil, barrels per day	35
Gas, MCF per day	39

In general, two or more of the foregoing listed factors are used in combination in an intrapool formula, depending upon individual pool characteristics and equity considerations.

Kansas

Allocation between pools: Productivity and acreage are used for fields whose total productive capacity is greater than market demand. Allocation is automatic, to a large degree, through a log-graph procedure.

Allocation within pools: Largely on the basis of productivity and acreage; however, not more than 30 acres can be allocated to any one well.

Louisiana

Dowd indicates that allocations by the Department of Conservation among pools *within the state* are based on depth, each field being given a maximum allowable determined by wells times depth allowable. The table of depth allowables is as follows:

Depth (ft.)	Pre-well allowable
0 to 2,000	76
2,000 to 3,000	90
3,000 to 4,000	109
4,000 to 5,000	128
5,000 to 6,000	151
6,000 to 7,000	177
7,000 to 8,000	204
8,000 to 9,000	228
9,000 to 10,000	261
10,000 to 11,000	295
11,000 to 12,000	330
12,000 to 13,000	365
13,000	410

The base allowable of the field may be further prorated among wells *within the field* by methods indicated in Table 3, which applied to 198 prorated fields in late 1947.

Michigan

W. B. Berwald,* under date of October 1947, reports:

"Regulation of oil production is by state regulatory bodies with the assistance of an advisory board to the supervisor of wells and of individual operators themselves. Natural-gas production is regulated by the Michigan Public Service Commission, and is separate from oil regulation procedure. Inasmuch as a consideration of physical waste is the only statutory authority for the regulation of oil production, and as demand for oil has generally exceeded supply, cooperation of the various parties participating in the regulation of production has resulted in individual field rates as high as possible without waste. With perhaps a few exceptions, allocation between fields has been unnecessary, except possibly to make per-well allowables more uniform in prorated fields. Allocation to individual wells has been on a per-well basis; and, as spacing regulations have been strictly enforced, allocation has been equivalent to acreage allocations. There has never been any modification of well allowables for potential, sand thickness, structural position, or other factors. During the war, when spacing was changed from 20 acres to 40 acres, the 40-acre well allowables were 1.75 times the 20-acre well allowable. In view of the limited supply, and to encourage exploratory drilling, discovery wells are not prorated so long as there is no physical or market waste. Several wells may be drilled in a new field before official proration orders are issued."

*The Oil Company, Findlay, Ohio.

Mississippi

During 1948 legislation became effective creating a Mississippi State Oil and Gas Board. This five-member board has the power to hold hearings, issue and enforce rules and regulations adequate to prevent waste, and also fairly and equitably to allocate production among pools and within pools. The members of the board are appointed—three by the governor, one by the lieutenant governor, and one by the attorney general of the state.

TABLE 3. Probable fields for which allocation orders have been written.

December 23, 1947
LOUISIANA

Allocation method	Number of fields	Per cent of fields
Basic (depth bracket only)	160	80.9
Acreage	26	13.1
Well and acreage	2	1.0
Acre-pounds	6	3.0
50 per cent acreage and 50 per cent potential	1	0.5
50 per cent acre-pounds and 50 per cent potential	1	0.5
50 per cent well and 50 per cent bottom-hole pressure	1	0.5
University Field (see Table 4)	1	0.5
	198	100.00

TABLE 4. University field—allocation methods by sands.

Allocation method	Number of sands	Per cent of sands
Acreage	5	41.67
Acreage and potential (per cent varies with lifting methods)	1	8.33
Basic	5	41.67
Special (in exception to order No. 45-I)	1	8.33
	12	100.00

At this writing (September 1948) statewide rules and regulations and proration orders have not as yet been published, so that the actual factors which will be used in allocation are not known. However, the law creating the board specifically prohibits the use of market demand as a method of allocation to the various pools and fields or to the tracts within a pool.

Preliminary proposals indicate that acreage will be an important factor in allocation within pools, and that MER is being considered as a major factor in allocation among pools.

New Mexico

Allocation between pools: The overall state allowable for New Mexico is determined by the Oil Conservation Commission, which consists of the governor, state land commissioner, and the state geologist. It determines this allowable largely on the basis of market outlet and market demand, and is reported also to consider the ability of the various pools to produce without excessive waste. It is not clear how this latter factor is determined.

Fields in the northwestern portion of the state are permitted to produce without restriction. Fields in Eddy, Lea, and a portion of Chaves Counties are subject to proration which works automatically once the overall state allowable has been determined. Total marginal production from wells incapable of producing the daily state top allowable within their depth bracket is first determined from previous production reports and nominations, and is deducted from the total state allowable set by the commission. The remainder is divided by the number of 40-acre units capable of making their allowables, and this quotient then becomes *the daily state top allowable*. In addition, a depth factor is introduced which modifies the allowable for deep pool units. Table 5 gives these proportioning factors.

The allocation to any pool, therefore, becomes the total number of top allowable producing 40-acre units times the daily state top allowable (modified by the depth factor if producing below 5000 ft) to which is added the marginal allowables from those wells unable to make top allowable.

TABLE 5.

Pool depth range (ft)	Proportional factor
From 0 to 5,000	1.00
Below 5,000 to 6,000	1.33
Below 6,000 to 7,000	1.77
Below 7,000 to 8,000	2.33
Below 8,000 to 9,000	3.00
Below 9,000 to 10,000	3.77
Below 10,000 to 11,000	4.67
Below 11,000 to 12,000	5.67

The only factors used in interpool allocation are producing acreage and depth.

From an engineering viewpoint, the use of only these two factors might be seriously questioned, however, in practice the system has worked well and the operators as a whole have been well satisfied. Wide spacing and relatively low allowables have been effective in preventing any glaring inequities.

Allocation within pools: Within any one field, adjustments are made for high gas-oil ratio, and such wells are penalized. The penalty oil is reallocated within the same field to other wells capable of producing it without excessive ratios.

Some fields have intrapool allocation formulas which have factors other than "producing units" (acreage). In Monument Field the allowables are determined 80 per cent on acreage and 20 per cent on bottom-hole pressure in excess of an average base. In Hobbs Field the factors are 80 per cent acreage and 20 per cent on the actual observed bottom-hole pressures. In most of the other fields except for the gas-oil ratio adjustment, allocation to the individual units is on the basis of acreage alone.

Spacing has given little or no problem in New Mexico, the 40-acre proration unit having been established early, and only in very shallow pools has there been any drilling at greater density than one well to 40 acres.

As indicated previously herein, although the proration system may not be so well designed from an engineering standpoint as might be desired, it has proved to be satisfactory to the operators. Its automatic feature has made it possible for each operator to calculate what his allowable will be, and the depth allowable has encouraged the exploration for and development of deep production.

Oklahoma

H. H. Kaveler* contributes the information on Oklahoma:

"*Establishment of pool allowables:* Pools in the state of Oklahoma are classified as 'allocated' or 'non-allocated.' There is no minimum well allowable fixed by law in the state. Each month the Corporation Commission, upon hearing, determines both the current market demand for oil and gas, and the amount of that demand that can be produced without waste and without unreasonable discrimination between allocated pools. In fixing daily production of an allocated pool in any month, the proceeding does not take the form of fixing a 'MER' rate as such. The allowables each month are determined by conditions currently existing.

"*Allocation within pools:* Production is allocated to individual wells under the general rules of the Corporation Commission. Factors considered in determining the allowables of individual wells within a pool are 'per-well,' potential, productivity indices, acreage in the drilling unit, thickness of pay zone, bottom-hole pressure, producing gas-oil ratio, and producing water-oil ratio. Practically, every allowable is based upon the fixing of a basic allowable, subject to a limiting gas-oil ratio—with the order written in such manner that production is permitted daily up to a fixed number of barrels of oil, or fixed number of cubic feet of gas, whichever first occurs.

"Since most of the pools in the state are uniformly spaced under the provisions of the well-spacing law, allocation for all practical purposes amounts to allocation on a drilling-unit acreage basis except for wells penalized for excessive gas-oil ratio or water-oil ratio.

"*Features of Oklahoma conservation practices:* The Oklahoma law provides for the fixing of drilling units of uniform shape and size, with wells drilled thereon on a uniform pattern throughout the pool. After the Corporation Commission (upon hearing) finds and orders a spacing program, the separate ownerships, both working-interest and royalty-interest, in each drilling unit so fixed, are automatically consolidated—with the commission given the power and authority to fix the termination of the 'operating agreement' between the parties in the event the parties cannot mutually agree thereto. The reasonable and constructive administration of this statute has done much toward effecting a greater measure of conservation practice, and has minimized the drilling of unnecessary wells in the state.

"An effective provision of the revised spacing law is the provision that prohibits the drilling of any well into any common source of supply during the period that an application for spacing is pending before the commission, except that such wells be drilled after hearing and the granting of an exception by the commission.

"Oklahoma has given much attention to gas conservation. This is accomplished by fixing gas-oil ratio limitations in all newly discovered fields and in many of the older fields. The conservation of gas is also effectively accomplished under a general rule of the commission that all 'discovery wells' are automatically granted

*Phillips Petroleum Company, Bartlesville, Oklahoma.

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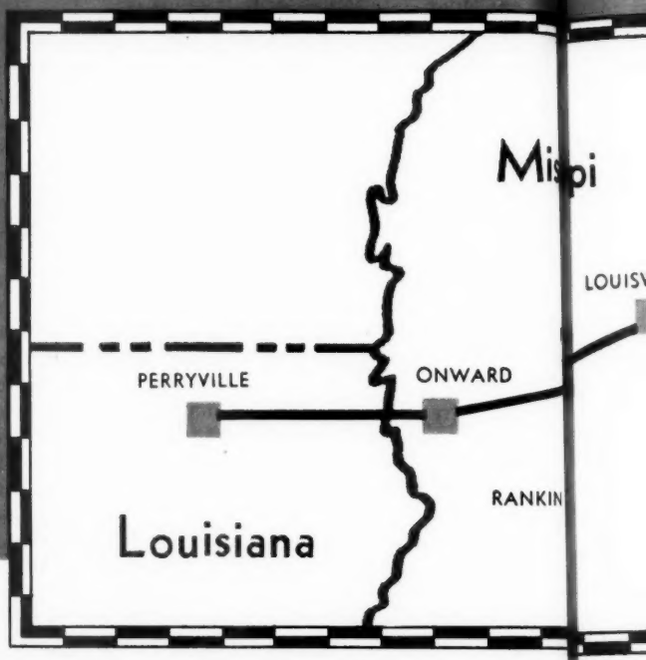

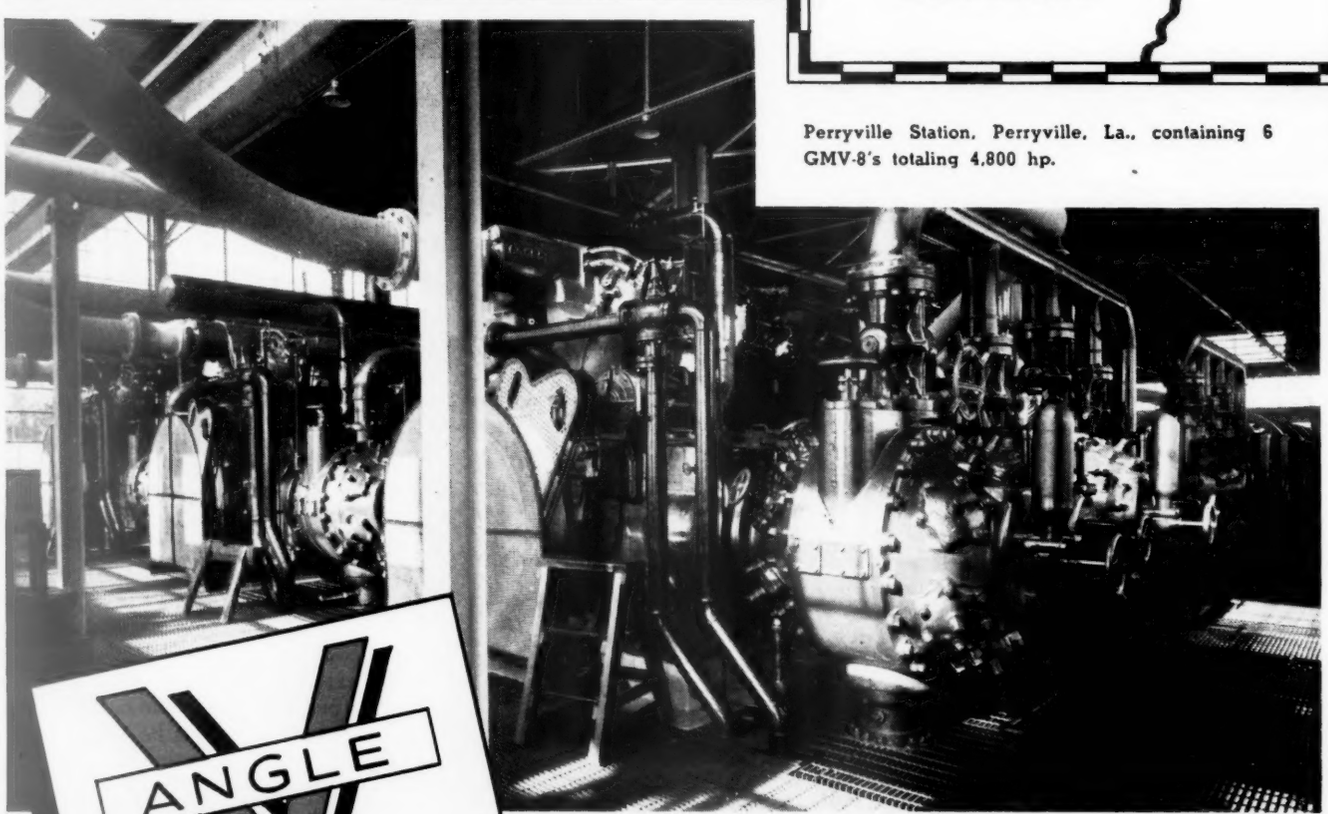

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a 'discovery allowable' of 150 bbl per well daily of oil, or 500,000 cu ft of gas daily, whichever is first produced. Such discovery allowable remains in effect for a period of 60 days from the date of first production—after which it is automatically terminated, unless the operators present to the commission, in hearing, evidence upon which an allowable can be fixed after that 60-day period. Such a discovery allowable rule encourages the operator to obtain basic and essential information on discovery wells to the point that a conservation program can be designed from the beginning of production.

"The Corporation Commission in recent orders has adopted the principle of fixing allowables as between tracts, on the principle of granting 'equivalent volumetric withdrawals' from the reservoir to each separate drilling unit. This, in fact, is the principal factor in setting the limiting gas-oil ratio which fixes the maximum production from any allocated drilling unit.

"The state of Oklahoma continues to lead in the adoption of effective conservation practices. This is again demonstrated in the 'pool unitization law,' created by House Bill 339 of the 1945 legislature. Under this statute the commission, upon hearing and upon finding in the absence of veto of the order by 15 per cent ownership in acreage, may order the unitized management and operation of any common source of supply when it is found necessary properly to utilize reservoir energy and to obtain the maximum ultimate recovery.

"On July 28, 1947, the Oklahoma Corporation Commission, acting under House Bill 339 of the 1949 legislature, approved a plan of unitization for the West Edmond Hunton Lime Field. The West Edmond Hunton Lime Unit operation became effective October 1, 1947. It was followed by the formation of the West Cement Medrano Unit on December 1, 1947, and by the Southwest Antioch Gibson Sand Unit on April 1, 1948, and by the granting of an order forming the Chitwood Unit effective on March 29, 1948. Each of these unit operations will substantially increase ultimate recovery of oil, and accomplish the conservation of a large reserve of gas."

Texas

T. A. Huber* reviews in detail present trends in allocation in Texas.

"*Allocation among pools:* The Texas Railroad Commission, a body of three elected commissioners, regulates production in the state. For the more important fields, MER is the controlling factor in allocation to pools. Allocations are essentially on a uniform percentage basis of field MERs. For the smaller fields on which the Railroad Commission has not set MERs, the old 'yardstick' of depth and acreage still applies to a considerable extent. MERs are determined after Railroad Commission hearing at which all operators have the opportunity of presenting evidence. New wells in new fields continue to have discovery allowables that are dependent upon depth and MER.

"The Railroad Commission in establishing MERs has held public hearings for the stated purpose of determining 'the highest productive capacity that can be obtained without causing preventable waste.' The commission has required the submission of data on reservoir pressure, gas-oil ratio, salt-water production, and rate of oil production; these data to reflect, where available, average reservoir values for each reservoir, and preferably to be submitted for periodic intervals during the producing life of the reservoir or, at least, to cover periodic intervals during the immediately preceding four years. It is further suggested that additional information on each reservoir within a field, such as average porosity, average permeability, type of energy drive, and productivity indices be furnished if available.

"The commission suggests that operators in each field confer with each other so that such data may be assembled and presented with respect to reservoirs as a whole rather than with respect to particular leases, and that one operator be appointed to submit such reservoir data at the hearing. Each operator, however, is requested to submit his own recommendation as to the maximum efficient rate of production.

"Of the 1214 fields included in the Railroad Commission September, 1947 schedule, 483 (40 per cent) have been assigned MERs by the commission. The sum of the MERs for these fields, and including the East Texas Field, amounted to 2,047,000 bbl, compared with the state of Texas August daily average production of 2,306,000 bbl, or 88.7 per cent of the production. The MER total includes rates for a number of stripper fields that were established at or near their productive capacity, but which account for only a very small portion of the total MER.

"*Allocation within pools:* Table 7 lists the various methods of intrapool allocation in effect in 372 Texas fields for which allocation formulas have been prescribed. For these fields, there has been only one order prescribed since January, 1943 that did not give 50 per cent or more credit to acreage. Only 2 formulas have been used during 1946 and 1947, viz., 50A + 50W and 75A + 25W. These 2 formulas account, respectively, for 63 (50 per cent) and 57 (45 per cent) of the total of 126 allocation orders prescribed since January, 1943. It is noteworthy that for only 15 of the 372 fields there is given no credit for acreage. Omitting 7 fields with slightly different bases of allocation, the distribution in order of credit given to acreage is as in Table 6.

TABLE 6.

Acreage in formula (Per cent)	Number of fields
25	8
33⅓	7
50	177
60	4
66⅔	2
75	116
100	36

"The remaining credit was distributed in varying proportions among wells, bottom-hole pressure, and potential factors—with the well factor predominating. Considering the formulas adopted during the past few years, it appears that acreage and other such volume factors are at least holding their own or gaining slightly in consideration.

"Although there has been a trend away from the use of potentials as a basis for allocation, with two formulas employing potential factors rescinded during 1947, there are still three based wholly on potential, and 47 others include a potential factor. Twelve fields use bottom-hole pressure in the allocation formula. Among the miscellaneous categories are one field allocated on the basis of reserves and one each having factors for depth and acre-feet. The usual consideration is given to marginal and high gas-oil ratio producers, and suitable corrections made.

"*Important changes and decisions affecting allocation formulas:* During 1947 several decisions and innovations in allocation formulas took place which may have an important bearing on future formulas. Noteworthy were: *a*, the adoption of formulas at Stratton and Old Ocean which permit owners of gas caps overlying oil zones to have current income without dissipation of the gas cap before the oil is recovered; and, *b*, the Hawkins proration suit to obtain relief from drainage of oil to a densely drilled townsite.

"*Stratton allocation order:* The Bertran and Wardner oil reservoirs of

*Humble Oil and Refining Company, Houston, Texas.

	RECOMMENDED							NOT RECOMMENDED			
	ACREAGE	BOTTOM HOLE PRESSURE	SAND OR PAY THICKNESS	RESERVES	MARKET DEMAND	DEPTH	MER	PRODUCTIVITY	PRODUCTIVITY INDEX	WELLS *	POTENTIAL
ARKANSAS	O	O		O	X		X			O	
CALIFORNIA	O	O	O				X O		O	O	O
ILLINOIS					X						
KANSAS	X O							X O			
LOUISIANA	O	O				X O				O	O
MICHIGAN					X					O	
MISSISSIPPI	O						X				
NEW MEXICO	X O	O			X	X O					
OKLAHOMA	O	O	O		X		X	O	O	O	O
TEXAS	X O	O	O	O		X	X			O	O
WYOMING ETC.					X					O	

* IF ALLOCATION IS TO WELLS – ON UNIFORM SPACING – EFFECT IS SAME AS ALLOCATION ON BASIS OF ACREAGE
X FACTOR USED IN ALLOCATION AMONG POOLS WITHIN STATE
O FACTOR USED IN ALLOCATION WITHIN POOLS

Note: An X should be shown in the "wells" column opposite Kansas.

FIG. 1. Allocation factors used in various states.

this field have large gas caps which have been cycled for a number of years. A unique proration order has been adopted for these reservoirs in an attempt to promote conservation by preventing dissipation of the large gas caps and at the same time to promote equity by permitting owners of gas-cap properties to secure current revenue. For oil operations, the order provides that ratios in excess of the solution ratio be penalized, and it requires return of all produced casing-head gas to the formation before the penalties are completely removed. For gas operations, the order permits production calculated to result in reservoir voidage per acre of gas cap equal to the reservoir voidage per acre of the oil zone. It is further provided that the Railroad Commission may permit voluntary conversion of the gas allowable so calculated to an oil allowable on an equivalent value basis, plus sufficient additional oil to compensate for the cost of lifting the oil if produced on the same lease, and also to meet royalty payments if produced on different leases. This order is in addition to that under which cycling operations are being conducted.

"*Old Ocean allocation order:* Cycling and oil-production operations are under way, with both the oil and gas interests of the operators being unitized. A Railroad Commission order issued August 20, 1947, for the Armstrong and Chenault sands of this field follows, in general, the pattern of the Stratton order but, in addition, provides that:

"1. Allowables of high gas-oil ratio wells may, at the election of the operator and with approval of the Railroad Commission, be transferred to any other well or wells producing from the same reservoir on any lease operated by himself or by other operators.

"2. Gas allowables of gas-cap wells subject to Railroad Commission approval may be transferred to any other gas-cap well producing from the same reservoir on any lease, whether operated by himself or others.

"3. A bonus allowable not exceeding one-tenth of the basic allowable will be given for injection of extraneous gas to the gas cap."

"'M. H. Dubrow* points out that Hildreth (No. 2 conglomerate unit) Field in Montague County, Texas, has operated under an order since December 1, 1946, which permits the entire daily oil allowable of the pool to be produced from the *most efficient wells.* The entire area of the unitized gas-injection project was considered to be one lease. This is thought to be one of the earlier orders which permitted transfer of allowables so as ultimately to benefit the entire pool and to allocate production to wells within the unitized area on the basis of engineering factors.'

"*Hawkins proration suit:* The allocation formula adopted by the Texas Railroad Commission for the Hawkins Field credits 50 per cent to acreage and 50 per cent to wells, with the further provision that a well on 20 acres (the proration unit adopted by the commission) will not produce more than twice the allowable of a well on less than one acre. With the exception of the Hawkins townsite, the field is drilled on a 20-acre pattern. In the townsite, an area of 73.7 acres contained 87 wells at the time of the suit. The formula allowed these 87 wells to produce 4147 bbl daily, or 9.3 per cent of the field allowable, although the 73.7-acre area contained only 1.5 per cent of the recoverable oil in the field.

"In the suit, a large operator and some owners of royalty in large tracts sued to enjoin enforcement of the formula upon the ground that it resulted in confiscation of their oil. Trial before jury in the district court resulted in a judgment decreeing the formula to be confiscatory and, therefore, invalid. However, the Austin Court of Civil Appeals reversed the lower court's judgment and upheld the formula. The appellate court held that, although the formula undoubtedly resulted in the drainage of plaintiff's properties, that fact was not enough to invalidate the formula, because the plaintiffs were compensated for the loss of oil by 'savings' which flowed from the 20-acre spacing rule. The court did not mention the royalty owners. The Texas Supreme Court and the U. S. Supreme Court have declined to review this decision." (See Table 7.)

*Continental Oil Company, Ponca City, Oklahoma, personal communication.

TABLE 7. Proratable fields for which allocation orders have been written, state of Texas.

	Nov. 1, 1947		Orders issued since Jan. 1, 1947	
Allocation method	No. of Fields	Per cent	fields	Per cent
P	3	0.81	..	..
W+P	8	2.15	..	..
M+P	3	0.81	..	..
W+depth	1	0.27	..	..
A+B	1	0.27	..	..
X+5 per cent A	1	0.27	..	..
25A+75P	1	0.27	..	..
25A+75W	7	1.88	..	..
⅓A+⅔W	2	0.54	..	..
⅓A+⅓P+⅓W	2	0.54	..	..
⅓A+⅓B+⅓W	3	0.81	..	..
50A+30B+20W	1	0.27	..	..
50A+50B	4	1.08	..	..
50A+25P+25W	2	0.54	..	..
50A+50P	24	6.45	..	..
50A+50W	146	39.23	12	43
60AP+40W	1	0.27	..	..
60A+40W	4	1.08	..	..
⅔AP+⅓W	1	0.27	..	..
⅔A+⅓W	2	0.54	..	..
75AB+25W	1	0.27	..	..
75A+25P	5	1.34	..	..
75A+25W	110	29.55	16	57
75A+25B	1	0.27	..	..
AH+B	1	0.27	..	..
100 A	36	9.58	..	..
Reserves	1	0.27	..	..
Total	372	100.00	28	100

A = acreage.
B = bottom-hole pressure.
H = sand thickness.
M = marginal.
P = potential.
W = well.
X = basic allowable.

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7
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FORGED STEEL SHEAVE . . with accurately machined groove for longer rope life. (Gaged with NEW wire rope gage.)
EXTRA HEAVY SHEAVE PIN . . . Induction hardened for resistance to wear; and accurately ground to size.
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Berwald's comments follow:

"Allocation of production among pools and within pools is essentially on a voluntary basis. Available oil production has often exceeded the demand and pipe-line outlet capacity. Production from individual pools has depended largely on market demand for the various types and grades of oil available. Allocation of production within pools has usually been on a per-well basis by voluntary agreement between the operators. Many pools are on lands subject to supervision by the U. S. Department of the Interior or by the various states, and these agencies participate to appreciable extent in the regulation of production. However, there is no legislation pertaining to regulation or allocation of oil or gas production in these states. Many pools are operated under unit plans, with acreage as a basis of participation and production controlled to obtain efficient recoveries from the reservoirs. In other pools, field allowables and well allowables are controlled by mutual agreement and cooperation between operators. In most pools, however, rate of production is as high as market demand and pipe line outlets will allow without excessive waste. Trends during the past two or three years have been toward more unit operations and more efforts to regulate production to obtain greater recovery efficiencies."

Summary

It would appear that acreage as a factor in allocation has been recognized in all of the states which attempt to allocate production. In many instances it is used without any other qualifying factors, as in the case of fields which are prorated on 100 per cent acreage. The use of a single acreage factor presupposes that all leases within a pool are underlain by the same quantity of oil per unit area. In most oil fields this would be an exceptional condition. When wells alone are used, and when a uniform spacing is adhered to, allocation is the same as it would be on 100 per cent acreage. If uniform spacing is not prevalent, allocation on the basis of wells alone tends to result in production on the basis of the "rule of capture" rather than to give to each operator his proportionate share of the "oil in place." The use of wells in a formula is usually justified on the score that an operator should be entitled to a return on the investment involved in drilling the well. When

this factor, however, becomes a significant percentage of the total allocation, then it encourages the drilling of unnecessary wells, as has already been indicated, merely to obtain additional allowable. The final outcome is either a poorly distributed drainage pattern or the drilling of unnecessary wells by all the operators in the pool.

Bottom-hole pressure as a factor in allocation is usually proposed as a means of avoiding undue pressure differentials between wells or leases, but the bottom-hole-pressure factor commonly employed is too small to prove effective in this regard. If the pressure factor is used in a formula as a multiplier rather than as part of an addition of factors, then its effect is more noticeable.

Engineers in general have concluded that potentials are not a direct measure of reserves under a tract or lease; they are, moreover, difficult to determine in such a way as to avoid discrimination. Even though taken under standardized conditions, they result in waste and fail to give to each operator an allowable rate of production which will return to him currently his share of the "oil in place." Its use in proration formulas is definitely decreasing.

Productivity index is used infrequently in California and Oklahoma, and then only as a minor factor.

Thickness of pay which, together with acreage gives a volumetric measure in an allocation formula, is used only to a very minor extent at this time. Increased use of this factor would do much to give engineering completeness to many of the allocation plans now in vogue. When volumetric formulas, either straight or modified, are used for allocation within pools in California, the "formation-volume factor" is included. In many other states an attempt is made to accomplish the same volumetric withdrawal by regulations which control gas-oil ratios or total gas production, water production, etc.

Inasmuch as the cost of a well is, in some measure, proportional to its depth, the use of the depth factor appears justified, provided the resulting production is not in excess of efficient producing rates. However, some economists argue that allocation should not be influenced by cost; and that, if it is necessary to drill deep wells in order to maintain our crude supply, then the market price of crude should reflect such added costs. This problem does not seem to be within the province of the engineer, and it appears that, under present conditions at least, depth might well be used in allocation of production between pools

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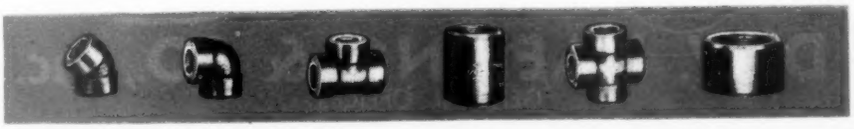

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to a greater extent than is now the case.

Maximum efficient rate is used in allocation between pools usually in an indirect way, in that it limits production of a pool. Its use as a direct method of allocation between pools has been somewhat delayed by the lack of satisfactory methods for its determination in all types of pools. California's determination and use of MER is outstanding. Texas now uses MER as an important factor in such allocation.

Reserves, although not often used directly, have some reflection in MER; and, insofar as that factor is used in allocation, reserves are represented. Considerations other than engineering sometimes prevent use of reserves as such in allocation plans.

Therefore, it is apparent that various states use all of the factors, summarized in the early part of this paper, which the committee has indicated might be used in an allocation plan. Unfortunately, they also use such factors as productivity, potential, and wells—which the committee does not strongly recommend and, in fact, condemns under certain conditions. It would appear that progress might be made in the way the factors are used, rather than in further complicating allocation plans by intricate formulas which include many factors. A greater use of multiple, rather than additive, formulas would tend more nearly to give the desired result, viz., when possible to give to each operator currently his proportionate share of the oil in place within the reservoir.

Fig. 1 shows graphically the factors used in various states in allocation of production among pools and within pools. It emphasizes the fact that improvement in allocation practices can still be made. During the present period of high demand, with the attendant decrease in need for unduly severe restriction of production, proration and allocation become a minor problem. Its study at this time from an engineering standpoint is especially desirable, because the heated controversy concerning proper factors has cooled apace with the easing of urgency. The time may again come, however, when restriction of production will be necessary—not only as a conservation measure, but to balance production and market demand, and for the purpose of avoiding waste because of excessive overground storage. It is hoped that at such time factors used in all the oil-producing states will reflect careful engineering study and recommendations.

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1. "*Essential Engineering Factors in the Allocation of Production*," revised progress report and special papers by the Tropical Committee on Allocation of Production of the Central Committee on Drilling and Production Practice, Chicago, Illinois, October 26 (1933) and Dallas, Texas, November 14 (1934).
2. Progress reports of API committees on well spacing, submitted to the Institute's 8th Mid-Year Meeting, Wichita, Kans., May (1938).
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5. *Standards on Allocation of Oil Production Within Pools and Among Pools*, by the Special Study Committee and Legal Advisory Committee on Well Spacing and Allocation of Production of the Central Committee on Drilling and Production Practice, API Division of Production, published by the Institute (1942).

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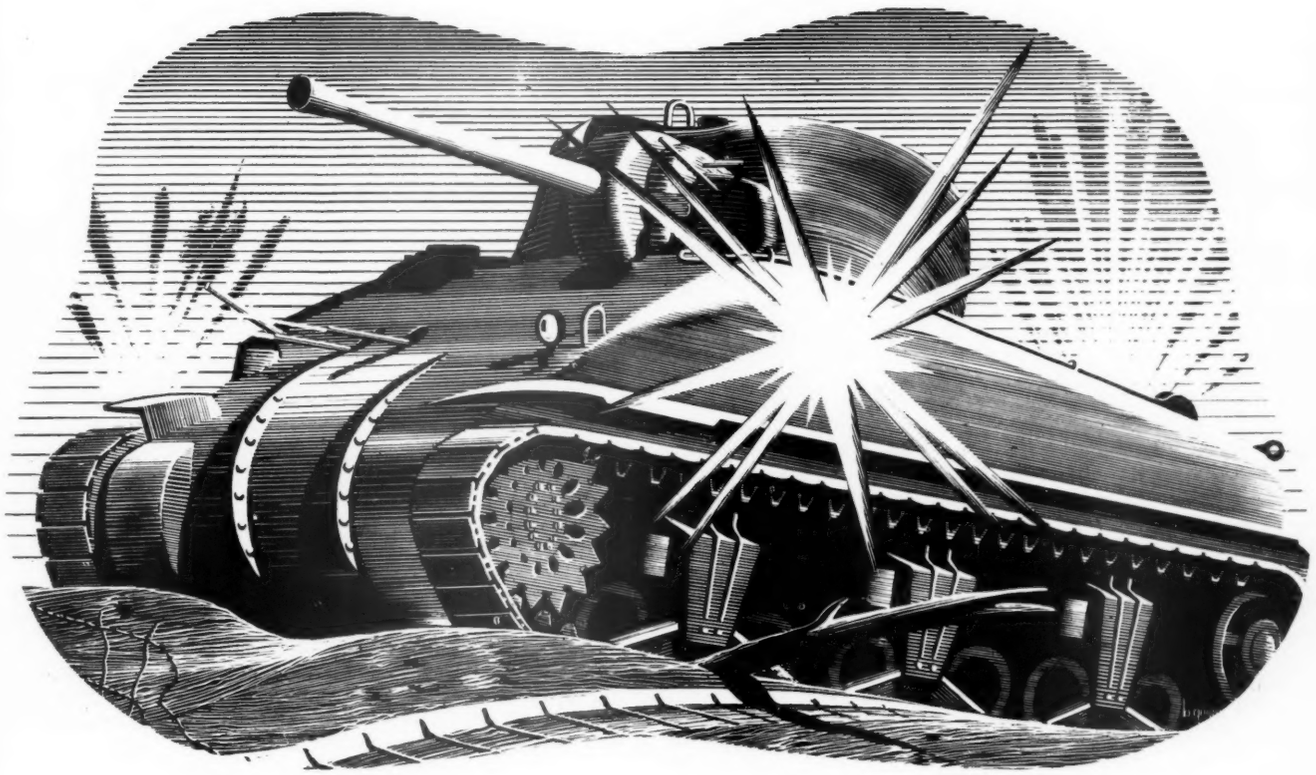

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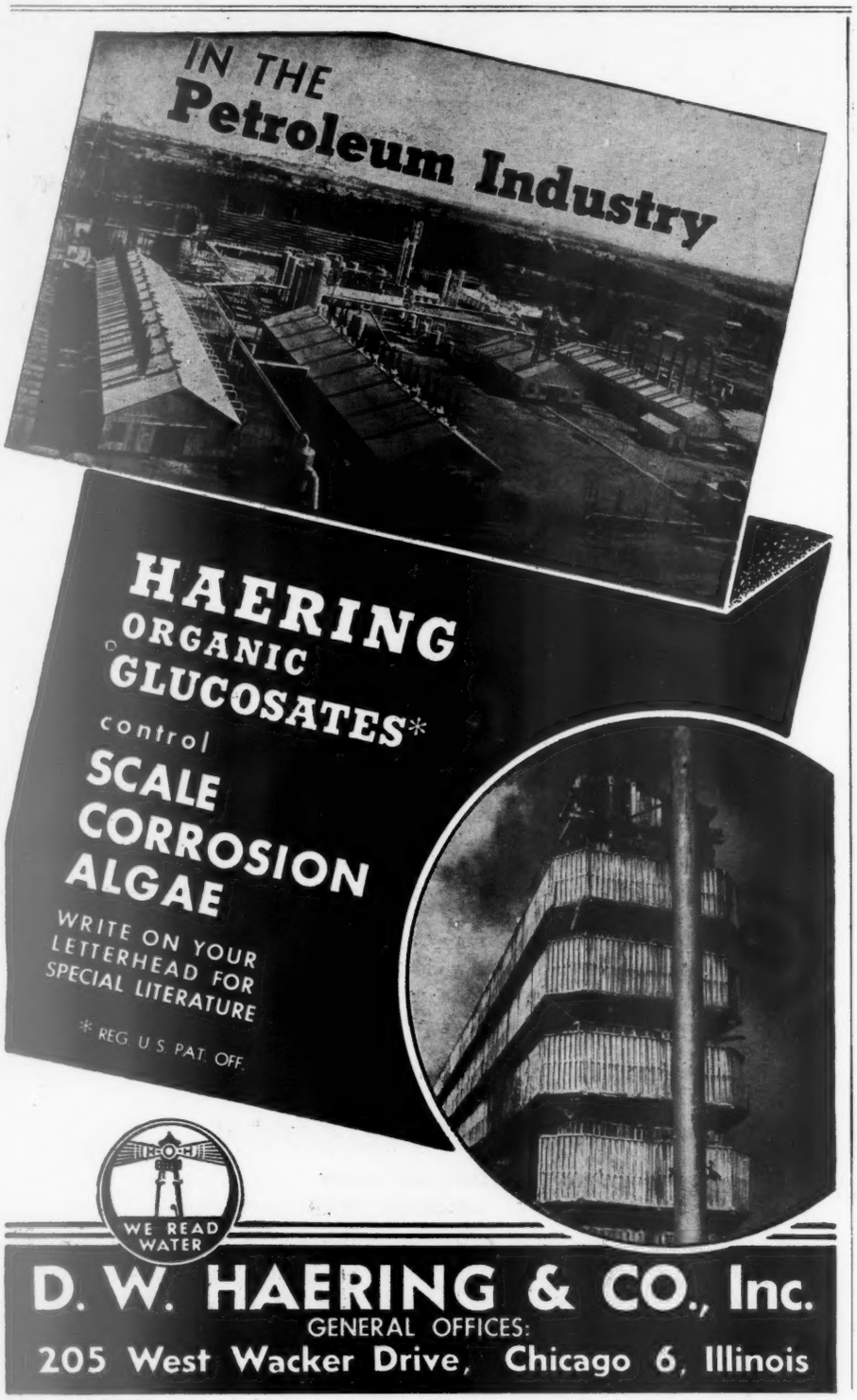

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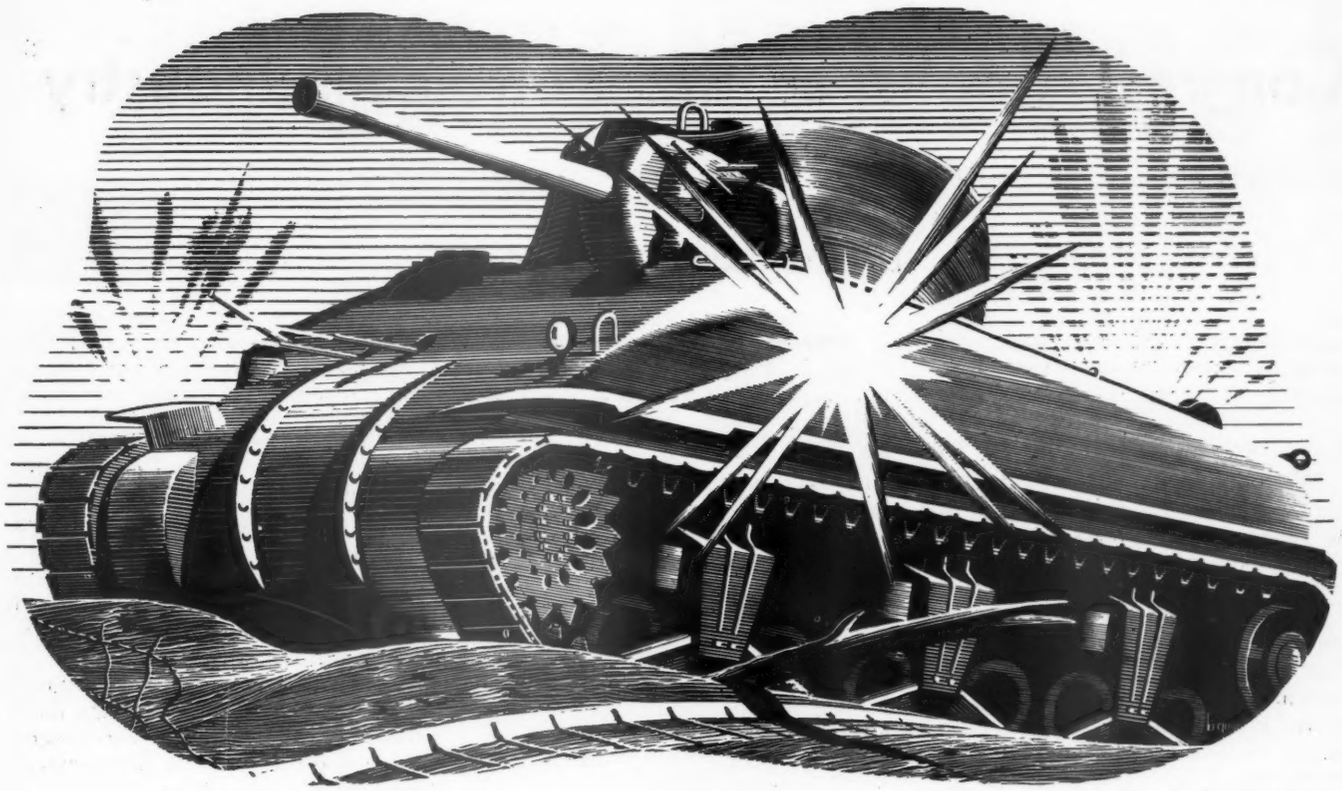

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Congress Looks at the Petroleum Industry*

SENATOR GEORGE W. MALONE†

CONGRESS is uncertain and undecided about the future status of the oil industry.

Facts—Not Opinions

The individual Senators and Congressmen need factual information on the *fuels position of the United States* —more now than at any time in the history of this nation.

They do not need opinions—they need facts, upon which a sound decision can be based relative to the fundamental question of how best to assure this country of an adequate supply of petroleum fuels in time of emergency.

The Congress, of course, is convinced that only the immediate and continuous availability of an adequate supply of petroleum fuels could win a third World War.

Competitive Business Methods Most Effective

The Congress is further convinced that there is little question but that the lowest cost and greatest quantity of petroleum and petroleum fuels can be produced through the competitive business system—owned and controlled by the men who survive and build up successful producing and marketing organizations through their energy, endurance and know how.

The Congress also knows that the phenomenal success of the oil industry in keeping pace with the public needs over the past forty years has been largely due to rewards in profits to investors—investors who were willing to gamble in exploration and "wildcat" drilling operations—where the risk was great—but the rewards were also great when new fields were discovered.

No Shortage of Fuel in the United States

Your Congress also knows that there is no danger of a shortage of fuel in this country under any conditions, since it is well known that there is an adequate supply of coal for several hundred years.

Emergency Petroleum Fuels

The vital question has been raised, however, about how best to assure an adequate supply of petroleum and petroleum fuels for an emergency, such as a third World War for naval and other purposes where coal alone will not suffice; whether to slow down production, thereby saving our visible supply of petroleum for such an emergency, or to continue our heretofore successful method of increasing production and reserves, where a large share of the profits are continually plowed back into the business for exploration and prospecting for new fields and further supplies.

Your Congress knows that as early as 1922 a government bureau—the U. S. Geological Survey—estimated the entire oil reserves of the United States at 5 billion barrels. We know that 25 yrs ago our files were full of very learned reports, estimating that our oil supply would be exhausted within five to ten years.

Your Congress also understands that the petroleum industry operating under our competitive business system and governed by supply and demand, has supplied the nation's increasing demands for petroleum fuels since the 1922 five billion barrel reserve estimate—and continually increased such reserves until at this time it is estimated by the same government organization that we have more than 23 billion barrels of known petroleum reserves.

More Than 1000 Years of Synthetic Fuels

We also know that we have more than 100 billion barrels of synthetic petroleum fuels in known deposits of oil shale which can be made available in the form of petroleum fuels through proven processes when the economic situation justifies their development.

We also know that engineers and scientists now estimate more than 1000 years' supply of such synthetic petroleum fuels can be made available from coal using methods now nearer the commercial state of production than was synthetic rubber at the start of World War II. As oil becomes more valuable, synthetic sources of petroleum fuels will be utilized by commercial companies.

Two Important Problems

The Congress of the United States needs the facts and the best possible advice then on two pressing and vital problems:

1. Is it possible for this nation to run out of petroleum and petroleum fuels—considering all possible domestic sources of such fuels?
2. What agencies—the government bureaus, or experienced private business concerns should be encouraged to develop the synthetic fuels beyond the pilot plant stage?

Public Confidence Shaken

Public confidence has been shaken in the men and operating companies in the oil industry through investigations and government bureau reports —and claims that we are running out of oil through excessive reckless use and development—and government bureau claims that we should save the known supplies for an emergency—presumably World War III—and that many of the methods employed by such men and operating companies were not in the public interest.

The petroleum industry, vitally important to our national security and to our national economy, has a real job to do:

1. To convince the Congress of the United States that the public interest is considered paramount in their operations and that they are responsible in safeguarding such interest.
2. That they are furnishing the Congress of the pertinent factual material on the fuels position of this country, together with the best long range production advice of which they are capable.

Three Basic Products

There are many indispensable products in times of peace or war. Three of the basic fundamental products are petroleum, rubber and steel, without which we cannot live in peace or fight a war.

The production of these three indispensable products are interdependent

*Presented before 28th annual meeting of the American Petroleum Institute, Chicago, Illinois.
†U. S. Senate (Nevada), Reno, Nevada.

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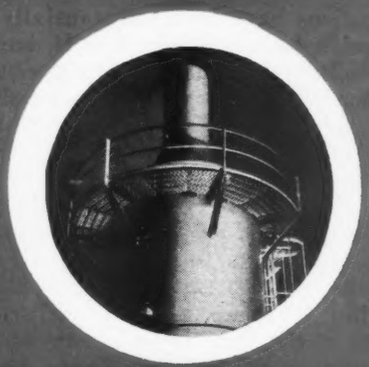

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and dependent upon each other for continued supplies:

1. We must have more available steel to assure the normal production, distribution and continued exploration and discovery of new fields and supplies of petroleum.

2. We must have an assured supply of petroleum for the needed production of synthetic rubber.

We are not running out of available iron ore for steel production, as has so often been currently reported in magazine articles, Sunday supplements and government bulletins by synthetic experts. There is currently known more available iron ore than this nation can use during the next 100 years—some of a slightly lower grade and some containing impurities which, however, the engineers know how to handle at a somewhat higher cost. This subject will be treated in detail at the proper time.

Steel—German Reparations and the Oil Industry

Congress also knows that the 7 or 8 million tons of steel being shipped to Europe annually could be added to the current 5 million ton annual production in Germany within 6 to 8 months through a simple executive order—and keep our own steel at home for use in pipe lines, tankers, tank cars, refinery and casing construction, and end the spot shortage of petroleum fuels in this country within 18 months. We could also start additional exploration drilling—making up some of the 70,000 wells which we are currently behind in such exploration work.

Most of the members of Congress know too that it is the German industrial plant reparations included in the much publicized Morgenthau plan, continually and currently supported by England and France, that prevents such an action being taken.

Congress knows these things through fragmentary information and data and through committee hearings, but it desperately needs complete factual information on the "Fuels position of the United States" from experienced men—experienced in the particular business about which they are offering such data and information—men in whom they can have complete confidence.

Domestic Petroleum Development and National Security

Many members of Congress cannot see how our national security will be safeguarded through retarding the further development of our domestic petroleum reserves as advocated by many government bureaus through their selective free trade principles adapted from the "1934 Trade Agreements Act"—and becoming dependent upon the Middle East for our petroleum supplies, when military authorities seem to agree that we could not hold that area against our potential enemies more than a few months at best and would then become dependent upon a hostile country for our fuel supply.

Confidence Between Business and Government

I am a freshman Senator—at least until the 81st Congress convenes in January. Therefore, I do not feel bound by any of the resentment or antagonism built up over the last two decades of business towards government—or of government towards business.

It is my firm and considered opinion that it is the responsibility of private business to conduct its affairs in the public interest in such manner that it will command the respect of the Congress of the United States—and that it is also the responsibility of the Congress to so conduct its affairs in such manner that it will command the respect of private business and the people whom it represents.

Mutual respect and integrity must be re-established and maintained. Without it we will drift further into restrictive legislation which will defeat our objectives.

National Policy

Congress must re-establish a definite national policy based on principle and law—instead of the hodge-podge of executive orders, department rulings and bureau regulations based upon the broad powers granted the executive department by the Congress of the United States.

As a result of such broad powers granted the executive department by the Congress of the United States, this country is now getting the greatest pushing around on the trade fronts of the world ever given a major power since recorded history, all of which vitally affects the petroleum industry.

This is almost entirely due to our juvenile approach to the entire subject of trade relations and a pathetic lack of understanding of the principle upon which we have built the greatest economic system, the highest standard of living and the strongest nation that the world has ever known.

Economic One Worlders—and American Industry

Congress, business and industry and the employees of such industries have given little consideration to the subtle procedure of the economic one-worlders.

The economic one-worlders, including foreign European banking firms, have been pressing their case quietly for many generations, yet only now after two devastating World Wars with the resulting unrest and confusion has their plan of dividing our markets and of leveling our standard of living with the low-wage Asiatic and European countries, taken definite and final form through the powers granted the executive department of our government by the Congress of the United States.

This is the greatest single factor tending to depress all business and industrial activity at this time.

Many of these foreign countries have had access to the same raw materials and resources for 2000 yrs, yet their people have made little progress in advancing their standard of living; while we have created the greatest production plant and markets in the world, largely during the past 70 yrs.

The economic one-worlders' complete plan, as adopted by the State Department, and recommended to Congress, for distribution of the wealth of the United States among the nations of the world includes:

1. Making up the trade balance deficits of the countries of the world in cash through gift-loans each year as exemplified by the recent Marshall Plan of 17 billion dollars to 16 European countries, and the English gift-loan of 3¾ billions of dollars a few years ago. This is entirely clear in the debate on the Marshall Plan in the Senate on March 4 and 5. Our chief export is cash.

2. Division of the markets of this nation through the selective "free trade" and the "horse trading" methods adopted by the State Department under 1934 Trade Agreements Act.

Under these trade treaties the tariffs of this country have been reduced from an approximate average of 45 per cent of value to less than 15 per cent, while the tariffs of competitive nations have been substantially increased since World War II, and in addition they utilize the quota system, manipulation of their money values, empire preferential rates and other subterfuges calculated to gain trade advantage.

Our markets are divided in this manner with the foreign countries on the theory that their trade balance deficits each year will be less in proportion. There is nothing reciprocal about the State Department's administration of the 1934 Trade Agreements Act—the phrase "reciprocal trade" does not occur in the 1934 Trade Agreements Act and is simply

OF OIL AND GAS INDUSTRY

Probably the most important development in the petroleum industry in recent years is the spectacular progress made in conservation measures. Modern repressuring, recycling and gasoline absorption plants save untold quantities of gas and oil, both for current use and for the future, that would otherwise be wasted.

Clark Compressors are playing a major role in this great enterprise. In 1948, over 100,000 BHP of Clark units were installed in Texas alone, for use in conservation projects . . . Big Angles, Midget Angles and Right Angles.

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In this plant near Beaumont, Texas, natural gas is gathered from the field, compressed and then put through an absorption process and natural gasoline is extracted. Residue gas is then utilized. Compressors are Clark 8-cyl., 800-BHP Right Angles.

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a catch phrase to sell free trade to the American people.

3. The proposed International Trade Organization, under which the 57 member nations of the United Nations—each with one vote—would meet at least once each year and estimate the remaining production and markets and frankly divide them among the nations of the world, eventually on a basis of population, completes the job of distribution of the wealth and markets of this nation with the nations of the world.

These are the methods adopted by the State Department with the announced purpose of raising the living standards of the countries of the world—the result, of course, will simply be a substantial reduction of our own.

It will be like deciding to average the level of the water in a water glass with that of the city reservoir—you may pour the water out of the glass into the reservoir until your glass will be empty, but the water in the reservoir will not be affected very much.

It is not an accident that the 1934 Trade Agreement Act was extended for one year, so that the second year Marshall plan appropriations—the 1934 Trade Agreement Act—and the International Trade Organization could be considered by the Congress of the United States all together—as they should have been in the first place.

A National Policy—the Flexible Import Fee

The flexible import fee method, first advanced by Congress in 1930 as a national policy, is a simple method of fixing such import fees on a scientific principle laid down by the Congress of the United States. It furnishes an automatic control of imports by furnishing a definite market for all foreign nations on a basis of fair competitive domestic costs and would guarantee a healthy-"going concern" petroleum industry for the security of this nation.

A fixed tariff has never functioned properly, since the economics of all nations are in a continual state of flux and while a tariff fixed today might correctly reflect the differential of cost of production—tomorrow it may be too high or too low.

A fixed tariff is a fixed tariff whether it is fixed by the Congress, the Tariff Commission, or by the State Department under the 1934 Trade Agreements Act, except that action by the State Department constitutes a treaty which cannot be changed except by consent of the nation which was a party to such treaty.

Under this method foreign countries, especially the empire-minded nations, have often depressed their own standard of living through manipulation of currency values or other methods, to come under our tariff structure.

Under the "flexible import fee bill" which I introduced late in the second session of the 80th Congress, the Tariff Commission would become the Foreign Trade Authority with full authority to determine the differential of the cost of production, based on "fair and reasonable competition."

The Authority would have ample jurisdiction to determine the proper import fee based on principles laid down in the bill which would then become the tariff or import fee—in the same manner as the Interstate Commerce Commission is set up to determine the proper transportation rates on interstate carriers.

Import Fee Does Not Retard Imports

An import fee, contrary to much recent propaganda on the subject, does not stop or unduly retard imports, but simply brings such needed imports in on our standard of living costs and would immediately establish a definite market basis in this country for the goods of the other 56 nations of the world. Under such a

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flexible system no advantage could be gained by any foreign nation through manipulation of its currency or by other methods.

Under this method every nation would be the judge of its own living standards, but would be encouraged to raise its own, since no advantage in trade with this country could be gained by holding them down, and when such standard in any foreign country approximates our own then "free trade" would be the immediate and automatic result.

The principle established under the flexible import fee bill automatically abolishes all "log rolling," lobbying, and "horse trading" methods, since neither Congress nor the State Department would have anything whatever to do with fixing such import fees—the Foreign Trade Authority would have sole jurisdiction under the principles established by the Congress —just as in the case of the Interstate Commerce Commission in transportation rates of the carriers.

Many members of Congress believe that the men responsible for the phenomenal development of the oil industry have done little to advance the adoption of national policies by the Congress and the executive department of our government to maintain our standard of living and national security.

The Fuels Position of the United States

Our National Resources Economic Committee, of which I am chairman, is at this time preparing a report—hearings will be continued on January 18, 1949—on the "Fuels Position of the United States." The committee has already published a report, "Minerals Position of the United States."

The fuels report will include the proven production areas of oil, gas and coal, together with areas of potential production where development and exploration can, and should logically be undertaken with reasonable expectation of success. The report will also include synthetic fuels, the production of petroleum and gasoline from oil shale and from coal, and the foreign sources of supply available to us under certain conditions.

Taxes

For 15 yrs the policy has been advanced to siphon off the increased wages and incomes through taxes to prevent inflation.

It is, of course, evident that such procedure did not prevent inflation—but did result in a serious reduction in the money normally available for venture capital investment.

Emil Schram, formerly with the Reconstruction Finance Corporation and now president of the New York Stock Exchange, recently indicated that the tremendous tax drain in this country is seriously threatening the venture capital investment market.

If the policy is continued, it is only a matter of time when the only source of venture capital investment will be our own United States treasury. We will then have reached the European nation's status—where government appropriations or gift-loans from other nations will constitute the only source of venture capital for new business and industrial investments.

It is my current opinion that the entire basic tax structure should be reviewed with a view of correcting this dangerous trend.

Tidelands

For nearly 100 yrs the shores of navigable waters and the soils under them were naturally taken for granted as the properties of the states, which include the rivers and streams systems of the nation.

The ownership by states was taken for granted and approved many times through the courts on the long accepted theory that any powers or authority not specifically transferred to the government of the United States were reserved to the states.

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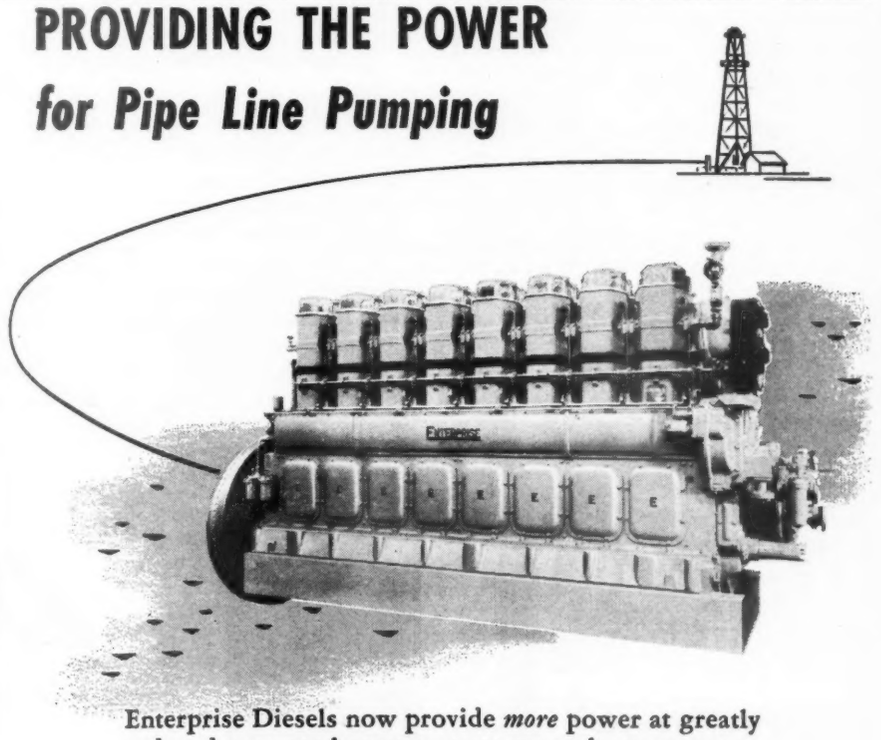

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tive departments of the government have applied this rule of property continuously during that time, and the government itself has in many special cases purchased and leased such lands from the states for federal use.

Even the Secretary of Interior in 1933 is credited with interpreting the law in relation to California tidelands to mean that:

"Title to the soil under the ocean within the three-mile limit is in the state of California and the land may not be appropriated except by authority of the state."

From an historical story of the situation, I think it may be reasonably concluded that the government of the United States filed suit in the Supreme Court to change this long-established ruling on the theory that the petroleum and natural gas under these lands were necessary for the security of the government and not on any basis of constitutional right.

This has been the plan of certain theorists for many years and all markets and production have been kept in a state of flux, with no definite national policy, purposely to bring about the desired result.

It is my firm opinion that the Congress of the United States should correct this trend.

Lack of Confidence Between Business and Government Dangerous

Nothing can be more dangerous to our business system of development and to our national security than a continued and growing lack of confidence between such business and industrial enterprises and the Congress of the United States, and only representatives of such enterprises and the individual members of Congress can re-establish the necessary cooperation and confidence.

The real danger to our form of government lies in foreign influences gaining a foothold while we bicker among ourselves on details.

National Policy by Law

No one can speak for the Senate of the United States—to say nothing of including the House side of that important body—but speaking as one member of the Senate of the United States, I believe that it is imperative:

1. That the men of the petroleum industry make every effort to re-establish the trust and confidence between business and industry and the Congress of this nation—through close cooperation in determining the "Fuels position of the United States."

2. That the men of the petroleum industry offer every cooperation to the Congress in establishing a national policy by law that will maintain our standard of living and national security, while we are assisting the nations of the world to establish their own.

Preserve the "Know How"—Cannot Run Out of Petroleum Fuels

Speaking again as one member of the Congress of the United States looking at the oil industry—I believe that we must preserve the energy—the restless drive and the know-how of the men who have created the oil industry through business investments, in order to insure our national security through the future adequate production of petroleum fuels.

The men of the petroleum industry can assist materially in preserving this relationship through cooperation with the Congress of the United States on the basis of the public interest.

Again, speaking as one member of the Congress of the United States, I believe that, except for continued undue government interference, it is simply a physical impossibility for this country to run out of petroleum fuels.

* * *

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ERP Petroleum and Petroleum Equipment Commodity Study*

Crude oil and petroleum products for European recovery are going into Marshall Plan countries in increasing quantities for industry and to aid in the development of road, sea and air transportation, the expansion of inland shipping, and the mechanization of agriculture.

According to estimates made by the Economic Cooperation Administration, the participating countries are expected to use 48.7 million tons of petroleum products in the fiscal year 1949-50. This is equal to about 975,000 bbl a day or 20,000 bbl a day less than was estimated by the participating countries. It is an increase of 57,000 bbl a day over the estimated 1948-49 consumption and 374,000 bbl over the prewar level of 601,000 bbl a day.

The importance of petroleum in the recovery program is emphasized in an analysis by the Organization for European Economic Cooperation of the manner in which the four principal petroleum products—gasoline, kerosine, gas, diesel oil and fuel oil—are expected to be used in fiscal 1950 compared to the prewar period.

For example, in the eight largest consuming countries, OEEC estimates that only eight per cent of all oil will be used for private motor cars and motorcycles compared to 21 per cent in the prewar period. In terms of total quantities, the amount expected to be so used is 33 per cent less than in the prewar period as a result of strict rationing in most of the countries.

Of total imports, ECA estimates that 21.8 million tons—nearly 436,000 bbl a day—valued at $562.5 million on the basis of November 1948 prices, must be obtained from sources which require payment in dollars, that is, from American oil companies. The ECA estimate is nearly one hundred million dollars less than the estimates submitted by the participating countries of requirements from dollar sources.

The petroleum equipment programs of the individual companies for 1949-50 can be evaluated only against the long-term programs of which they are a part. These programs, when added together would result in an increase in annual refining capacity in Europe from 27.5 million tons in 1948-49 to 65.7 million tons in 1952-53, and an increase outside Europe from 54.2 million in 1952-53, an over-all increase of 56 million tons.

*Review of report of U. S. Economic Cooperation Administration, March, 1949.

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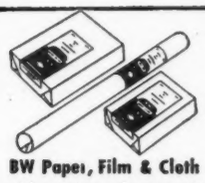

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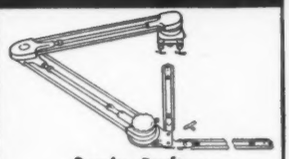

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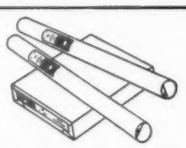

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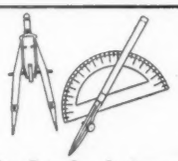

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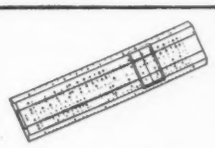

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The Petroleum Industry Looks at Congress†

FRANK M. PORTER†

IT is with some personal pride, as well as with considerable timidity, that I appear on this program with such learned and distinguished speakers. It is indeed an honor, which I deeply appreciate, to meet and talk with this great body of leaders of one of the greatest industries of the greatest country in the world. It is, however, a challenge which I must confess that I am inadequate to meet on the high intellectual plane to which this audience is entitled. However, with the inspiration of your presence and the understanding of your great capacity for sympathy, I shall undertake the responsibility that your program committee has placed upon me.

As a corollary to the splendid address of Senator Malone, "Congress Looks at the Petroleum Industry," my topic is "The Petroleum Industry Looks at Congress.† In this land of free speech, guaranteed to us by our Constitution, I can without the slightest fear of reprisals from my government speak frankly with respect to my Congress. I can praise the things about the Congress I admire and approve, and I can, with equal freedom, condemn and criticize those actions of which I disapprove. Such freedom is our American heritage, which we sometimes forget to appreciate. The same fundamental document under which we Americans live and which preserves for all of us this priceless freedom created the Congress of the United States and delegated to it certain prescribed powers, and as well it specifically withholds all other powers. These reserved powers are, and we hope they shall always be, vested in "we the people."

It has become almost a national pastime to "pan" the Congress. Whether the 80th Congress was the "worst in history" became a major issue in the national campaign terminated last week. It's an old American custom to condemn Congress for everything from droughts, floods, and crop failures to prosperity. Only a few days ago I heard the argument being made that Congress always let prosperity run away with the people and, therefore, it brought on the economic depressions that we have sometimes experienced in this country.

I am not familiar with the experience that other industries may have had with Congress; but, so far as the oil industry is concerned, I think it may be generally said that we have always looked upon Congress as a refuge of protection against the buoyant bureaucrats who live with that constant conviction that the management and operation of all business, and particularly the oil business, is a function of their particular bureaus. To date, I am happy to say, in my opinion, the Congress has done a reasonably good job of protecting the system of private enterprise and free competition under which the oil industry has developed and grown to occupy an important place in the American economy. Of course, there have been some breaks in the dike, and here and there a little bureaucratic power has seeped through. There have been times when it looked as if the flood water of bureaucracy might break through and engulf us.

It will be remembered that it was Congress that permitted the bureaucrats to sell them that well-known package labeled "NRA," and commonly known in the heyday of its Washington glorification as the "Blue Eagle." It was this mistake of Congress that resulted in a "federal petroleum code." This, in turn, produced a petroleum administrator who testified before a committee of the House of Representatives that, prior to becoming a member of the President's cabinet, he had never seen an oil well. Fortunately, the oil industry was delivered from the petroleum code by a Supreme Court decision holding that Congress had acted contrary to that basic document to which I referred a moment ago—the "Constitution of the United States."

Later came the Cole bill, which represented a most serious threat of the bureaucrats to assume substantial control over the oil industry. We took our case to the Congress, and there we tried out the merits of the proposal. The record made in those hearings will long stand as a monument to the heroic efforts of many members of the petroleum industry to defeat a partial nationalization of our business. Friends made in the Congress during those hearings have been lasting friends. Although the Cole bill was laid to rest more than 10 years ago, many men then in Congress, who have remained in public service, frequently express great confidence and respect for the oil business because of the thorough educational campaign conducted by the industry at that time.

On many occasions the oil industry has appeared before Congress to resist proposed laws that it believed would hamper its ability to discharge its full public responsibilities.

Seldom has the oil industry gone to Congress for affirmative relief. By and large, we have always felt that, if our system of private enterprise and free competition in business was preserved, the oil industry had within its own resources the ingenuity and ability to hold its place on the economic front.

Two years ago, when the smoke of the congressional elections had cleared away and when the oil industry made a critical examination of those representatives of the people who had been elected to serve them in the Congress, there was considerable rejoicing. After long years of attack from the Washington bureaucrats, and some in the Congress, we thought that now we may have peace and more time to attend to the business of finding, refining, and distributing more oil to the American people, and more time for building up a strong and healthy industry for the security of our nation. Two things in particular we deemed important. We felt justified in asking Congress to pass both measures—one was confirmation of the state's title to the tidelands because they appear to hold considerable promise for new oil discoveries, and the oil industry believed those lands could be best developed under the

*President, Fain-Porter Drilling Company, Oklahoma City, Oklahoma; president, Mid-Continent Oil and Gas Association.

†Presented before the 28th annual meeting of the American Petroleum Institute, Chicago, Illinois, November 8-11, 1948.

local jurisdiction of the states. The second measure would have clarified the natural-gas act which is being administered by the Federal Power Commission in such manner as to retard the production and transportation of gas into new markets.

During the war the oil industry dedicated itself, its manpower, its equipment, and all of its "know-how" to winning the war for America and our allies. During those war years the slightest wish of government was our command. Through the Petroleum Industry War Council and the Petroleum Administration for War, we worked hand-in-hand with government to the end that every facility of the petroleum industry would be most efficiently used for victory. Not only did we willingly assume this tremendous governmental responsibility, but we did not forget the responsibility of sustaining, petroleumwise, our domestic economy. I believe that it cannot be said that the war record of the petroleum industry is surpassed by any other industry in this country.

Attack on All Fronts

It was, therefore, the feeling of the industry that we could look to the 80th Congress with great confidence; but, to our consternation, and with some resentment, we were immediately beset by the greatest barrage of congressional investigations that has ever been visited upon any industry by any Congress. Not only did the Congress refuse to enact the tidelands bill and amendments to the natural-gas act, but seriously threatened to enact into law several bills that would have ability to carry on development of known resources or to explore for new reserves.

Anyone who followed, even casually, the deliberations of the 80th Congress and its investigating committees must have gained the impression that the oil industry was probably the greatest menace to the operation of a free economy in the country today. At one time, upwards of a dozen congressional committees were investigating various phases of the oil business or holding hearings on bills that threatened our very existence.

We were under attack on every front. Policies regarding conservation, production and supply of crude, competition, prices, profits, distribution, and transportation and supplies for the military forces, were under almost continuous attack by members of Congress and witnesses appearing before various committees from January 1947 until Congress adjourned in June 1948.

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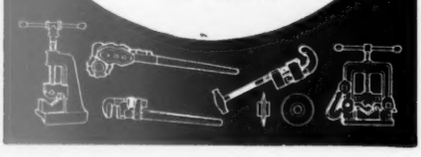

The situation was aggravated by the threat of a fuel-oil shortage during the extreme cold weather last winter. This was seized upon by some members of Congress as a basis of attack. It served to encourage all who had real or fancied grievances against the oil industry to air their views before the committees of Congress.

Obviously, in an industry of such importance to our economy and national defense there are bound to develop legitimate causes for criticism, but frequently charges leveled against the oil industry were exaggerated beyond all reason and with little or no evidence to support them. The publicity resulting from these hearings undoubtedly was harmful to the industry.

The fact that Congress did not enact into law any of the proposals calling for drastic controls or regulation of the industry is, of course, no assurance that similar attempts will not be made in the future. Several congressional committees were authorized to hold hearings during the adjournment period, and are planning to resume operations soon.

Our Rights as Free Men

It is natural that Congress should have a deep interest in an industry that is so farflung in its operations and which plays so important a part in our national economy, in our national defense, and which is so necessary to our welfare as the oil business. The industry can have no valid objection to legitimate investigations of its operations by the Congress, but it does have a right to insist that such investigations be centered in appropriate major committees, instead of being scattered over a dozen or more inquisitorial bodies all working at once and sometimes at cross-purposes.

We likewise have a right to expect that congressional utterances and findings shall be based on facts and corroborated evidence and not on mere conjecture, demagoguery, politics, and sensationalism. It is a well-established rule of American jurisprudence that the court and the jury are entitled to consider the credibility and the qualifications of the witnesses in weighing the evidence. I am sorry to say that congressional committees have not always done this. Many members of the Congress are prone to accept the statements of so-called government experts and bureaucrats as fact, simply because they occupy an official status. Many times the evidence of men who occupy the highest position of leadership in industry, and who represent years of experience in their particular lines of endeavor, seems to be completely ignored. I have in mind one report of a house committee of some 100 pages which quotes at length from the testimony of the government's witnesses, and not a single quotation from the long list of industry witnesses that appeared. We have a right to expect that the staffs employed by these committees shall be Americans who believe in the American way of life and who are familiar with the operations of the industry. We have a right to expect staff members who will approach their tasks with open minds, and not with preconceived notions about alleged evils of industry and with a desire to nationalize or socialize the industry regardless of the consequences.

We have a right also to expect courteous treatment from the committee members. On a few occasions members of congressional committees have forgotten their manners. It is a despicable display of arrogance for any member of Congress to use his official position to bulldoze or insult a witness who appears for the purpose of expressing his views to his public servants. Members of congressional committees who insist on doing all the talking seldom get much out of the witness.

It has been quite evident that some of the so-called experts who have influenced the attitude of congressional committees in the past have based their criticisms largely on the size of the companies involved rather than on any evidence of improper practices. It seems that to prosper and grow through serving the public has become a great evil. Perhaps the industry has been at fault in not meeting these issues head-on, and at the time when they were raised.

No one can dispute the fact that historically the oil companies have done a great job in supplying the oil requirements of this country, in both peace and war— and, I may add, always at fair prices. Yet almost daily on the floor of the last Congress, or in its committee rooms, demands for investigation of the oil industry continued to be pressed on what frequently was the flimsiest of charges. Meantime production of crude and petroleum products was breaking all records, and thousands of industry employees were working day and night to deliver oil and gasoline to their customers—sometimes in sub-zero weather under the most difficult of transportation handicaps.

Some Fallacies

This barrage of congressional attacks aided by a deluge of propaganda from the bureaucrats gave rise to the

belief by some that the solution of the alleged deficiencies of the oil industry was government control. How government management could add a single additional barrel of oil to the daily production has never been explained by an advocate of such a program; but, in the absence of organized opposition, it was accepted by congressmen as a likely improvement. This alarming attitude has been reflected in statements of members of Congress who ordinarily are regarded as champions of competitive enterprise and a free market economy.

During the last session of Congress the industry was not only met with the false claim that there was insufficient production to supply existing demands, but one congressional committee made the charge that the conservation laws of the principal oil states were designed to influence the price rather than to conserve oil. The truth is that the industry would not have been able to supply the oil requirements of the recent world war, nor could we prepare for another war, if these conservation practices had not been in effect in the several oil-producing states. It was also charged by this same committee that the industry, the state authorities, and the Bureau of Mines had entered into a conspiracy to cause the bureau to issue false estimates of demand, to hold production down, and to keep the price up.

Another charge constantly hurled by some members of congressional committees was that the larger oil companies discriminated against the smaller independent dealers in supplying refined products. This was repeated over and over during the threatened fuel-oil shortage. The fact is that many refiners severely limited their own outlets to accommodate competing distributors. No one can rightfully accuse the oil industry of unfair practices in this regard, when the true facts are known.

The oil industry is made up of more than 34,000 competing concerns, all searching for business under the rule of free competition. Each of them—large and small—is striving to provide better products and services at less cost than his competitors.

Congress was told repeatedly during the last session that prices of oil products were too high, and that the profits of the oil companies were exorbitant. Factually, the price of oil products has increased far less than prices of other commodities such as food, clothing, and furniture. As of August, the combined total of all items in the government's *Consumers' Price Index* was up 75 per cent over the 1935-39 average. By contract, gaso-

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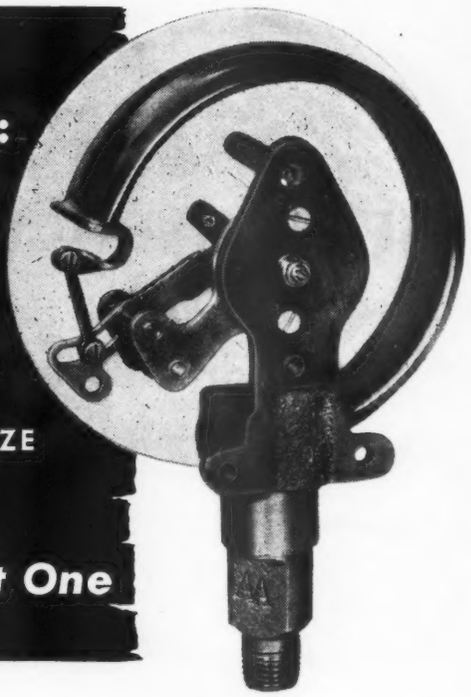

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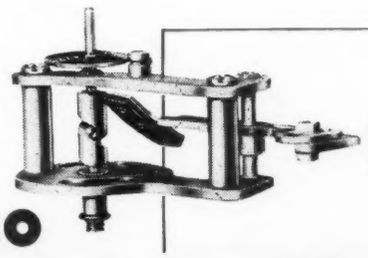

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line prices, *including* tax, increased only 34½ per cent during the same period. Motor-oil prices have advanced even less—about 20 per cent.

Congressional critics of the oil industry have pointed to similarity of prices and marketing practices among the larger oil companies as indicative of monopoly and price fixing or "monopolistic competition," as some of the new-style economists choose to call it. Every student of marketing knows that these conditions exist *because* of the intense competition in the industry. Each dealer must match the lowest price of his competitor or he will surely lose business. When any marketer of substantial size cuts his price, competitors must follow or lose business. On the other hand, when it comes to increasing the price of a product such as gasoline, nobody is willing to risk it unless he is convinced that the economic forces are such as to make the increase clearly justifiable and, therefore, likely to be followed by his competitors.

Another huge fallacy that seems to have taken root with some members of Congress and their expert advisors is that oil companies are continually holding down production to keep prices up and hold back new scientific development for the same reason. Actually, production figures are breaking all previous records, and they far exceed the most optimistic predictions. Since 1941 crude-oil production has increased 45 per cent, gasoline 35 per cent, and fuel oils 60 per cent. Oil companies are spending more than $100,000,000 a year on research to find new and better products and more efficient manufacturing processes. Competition in the research laboratories is as stiff as it is in the market place. No company can afford to take a chance on holding back scientific and technical development because of the risk that a competitor might discover it and profit from it first.

"Liquidating Dividends"

It is apparent from the reports of some committees that some members of Congress believe that oil profits are unconscionably high. Reported dollar profits these days are subject to a great many qualifications. Original cost is no longer a safe guide by which to compute replacement cost. Reported dollar profits would be drastically reduced if depletion and depreciation of capital facilities were figured at today's actual replacement cost. The same is true with respect to intangible drilling and development costs. It is perhaps technically correct to say that oil sold at $2.65 per barrel, which costs $1.65 to find and lift, returns a

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dollar profit; but we in the industry know that, if we are to stay in business, we must find as much new oil as we are selling. We know—because of deeper drilling, increased cost of material and equipment, increased labor costs, and more extensive geological and geophysical work necessary to find new oil—that we cannot replenish our crude-oil inventories at today's prices. Thus our big dollar profits become liquidating dividends.

Last year the oil industry used two dollars out of every three earned to replace and expand facilities in order to keep up and expand output. Let it be remembered that facilities purchased on today's market are costing from two to three times what they did prior to the war. As Mr. Sidney A. Swensrud, president of the Gulf Oil Corporation, has pointed out "... profits must be thought of in terms of what they will buy, just as wage rates, to mean anything in comparison with earlier levels, must be corrected by a cost-of-living index."

Perennial Scare Headline

Perhaps the greatest misconception that some in Congress have of the oil industry is that the country is running out of oil in the immediate future. This statement has been repeated by so many bureaucrats, and some in Congress, that it is beginning to take root in the public mind. This heralded fallacy has become a talking point of the politician, the demagogue, the bureaucrat, the socialist, and the communist who advocate government control of the industry. It was only 25 years ago that a governmental bureau informed a congressional committee that the oil reserves of the country amounted to approximately 5 billion barrels, or about 2½ years' supply at present rates of consumption.

Despite these prophets of doom, the American oil industry has since produced enough oil to meet the constantly increasing domestic demand

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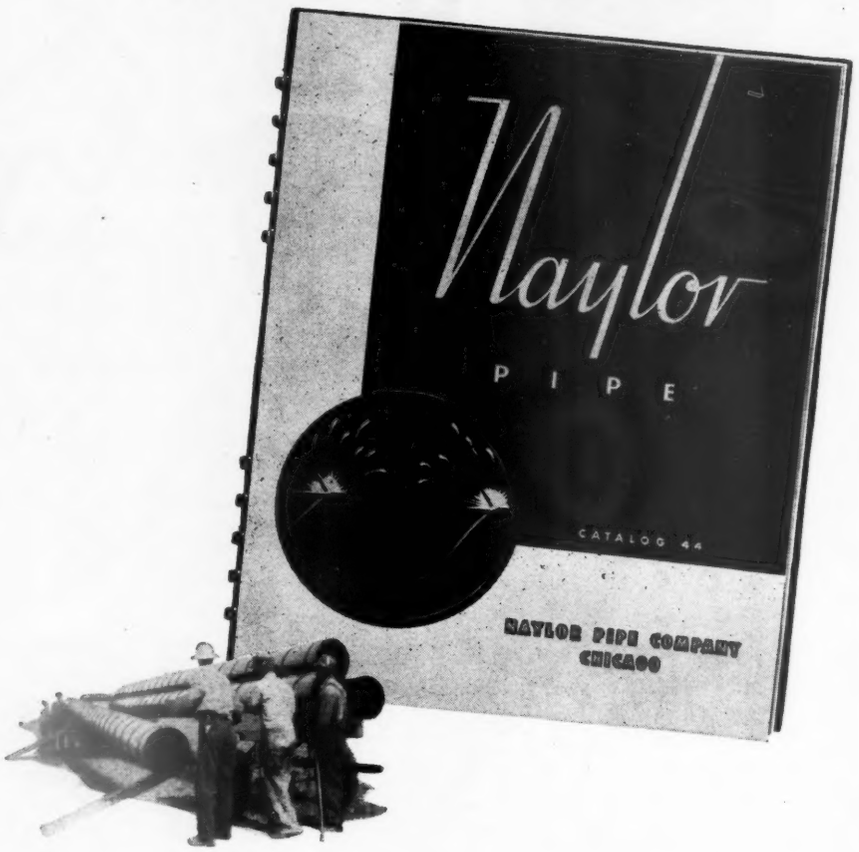

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and to oil another world war, with known oil reserves left in the ground equal to more than four times that estimated by the governmental bureau 25 years ago. The oil industry is discovering new and greater reserves day by day. With advancing technology for deeper drilling, for getting more and better products from crude, and for more efficient use, the American people are assured an adequate supply of petroleum products for the foreseeable future. The oil industry is not content to rest, however. It is unceasingly advancing its technical and scientific information for the development of synthetic fuels from gas, shales, and coal, if and when this should ever become necessary. This is a further guarantee that the oil industry recognizes its full responsibility in supplying the fuel needs of this nation.

How Come?

I sometimes wonder if members of Congress ever ask how it came about that Americans have found more oil and developed oil resources more rapidly and more extensively than any other people. It would seem worthwhile to seek an answer to these questions. If finding oil only involved the application of scientific knowledge, the use of skilled workmen, and heavy machinery, I doubt the Americans would excel.

Scientific knowledge has been developed to a high degree in other countries where skilled workers and machines abound. The prime requisite to success in oil finding is freedom to explore, as well as the freedom to develop and produce the oil once it is found. *It is in these freedoms that America does excel.* In our country every landowner can freely dispose of the oil under his land. In no other country on earth are oil resources so readily accessible to the wildcatter as in the United States. Unless American oil men had been free to drill exploratory wells at will, we could not have built this great domestic industry.

A careful look at our Congress leads to the inescapable conclusion that they are, in most cases, men of superior intellect and high patriotic devotion. It is my firm conviction that, if they are willing to be guided by the facts as submitted by competent authorities, both inside and outside of industry, and if they will follow their own sound judgment instead of listening to those who have axes to grind and who use congressional committees to exploit their own pet economic theories, the atmosphere for a continued healthy, growing oil industry will be preserved in this country.

* * *

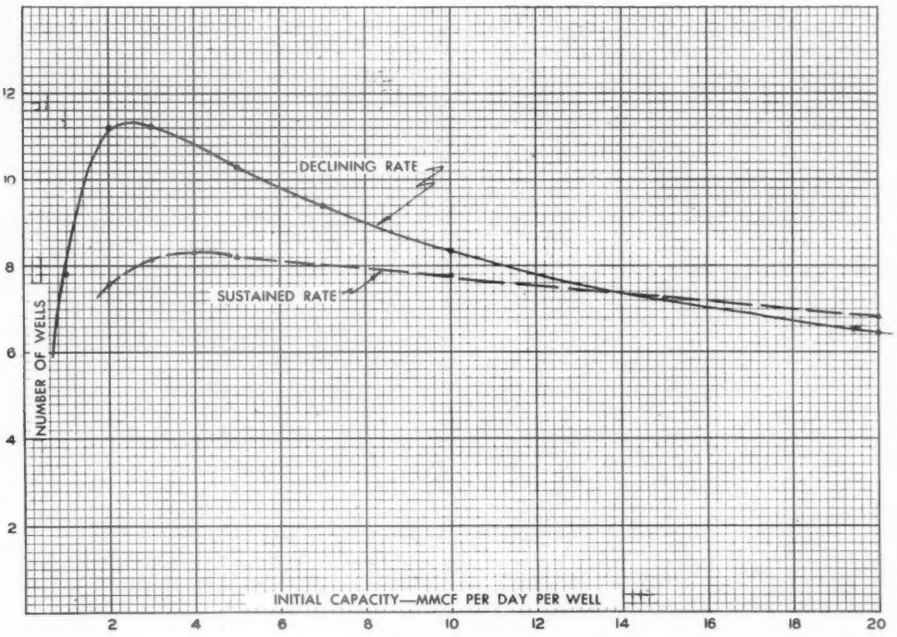


FIG. 1.

The Problem of Gas-Well Spacing†

D. T. MacROBERTS*

Abstract

Gas-well spacing is not dictated by physical recovery, but by economics. Theoretical calculations, based upon maximum recovery per dollar invested, indicates spacings very similar to those in use in the past.

The Physical Problem

THE spacing problem in natural-gas wells, from the physical aspect of ultimate recovery, can hardly be said to exist. Some years ago the author proposed a solution to this problem, which showed that the ultimate recovery from gas reservoirs was practically independent of the spacing for any reasonable well density; but, although the problem was explicitly stated as one in physical recovery, the solution was essentially an economic one, based upon abandonment pressures.

Upon further reflection, it is obvious that there is no problem of ultimate recovery in gas reservoirs as a function of spacing. Given sufficient time, a single well will drain any connected reservoir; there is nothing to prevent it. No dissipation of energy occurs as a gas flows through a porous reservoir body. The potential energy (pressure) is converted into kinetic (motion), but the reconversion to potential is complete as soon as flow stops. Any dissipation of energy into heat (friction) is transferred to the formation, which again gives it up to the gas.

The basic difference between the energy relations of oil and gas reservoirs is that, in gas reservoirs, the energy of the fluid accumulation is simply PV—the reservoir pressure times the volume of gas. This cannot be dissipated except by actual production of the gas. In oil reservoirs, on the other hand, the energy for expulsion of the oil is, in large part, exterior to the oil accumulation itself, and may be dissipated without attendant production of oil.

Because there is no ultimate recovery problem in gas-driven gas reservoirs, there is none in water-driven reservoirs. Production rates which are too high may fail to utilize fully the energy available in the water, but cannot decrease the ultimate physical recovery. As the edge water encroaches and inliers form, the reservoir itself breaks up into separate reservoirs—each of which must have a well for complete exhaustion and, in this limited sense, these can be said to be a spacing problem. Such spacings are obviously particular to the field, and cannot be generalized.

The well-spacing problem can, therefore, be returned to its true sphere, viz., economic.

The Economic Problem

Mathematical solutions to economic problems should be made only with the understanding that they are to be re-examined periodically to insure

*Union Producing Company, Shreveport, Louisiana.

†Paper presented to a meeting of the Special Study Committee on the Allocation of Production and Well Spacing, under the auspices of the Division of Production, during the 28th Annual Meeting of the American Petroleum Institute, in the Stevens Hotel, Chicago, Illinois, November 9, 1948.

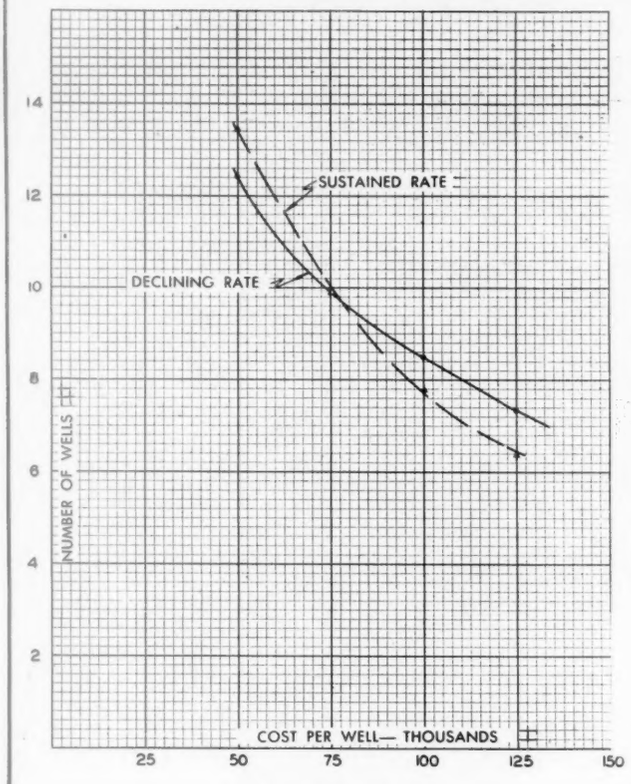


FIG 2.

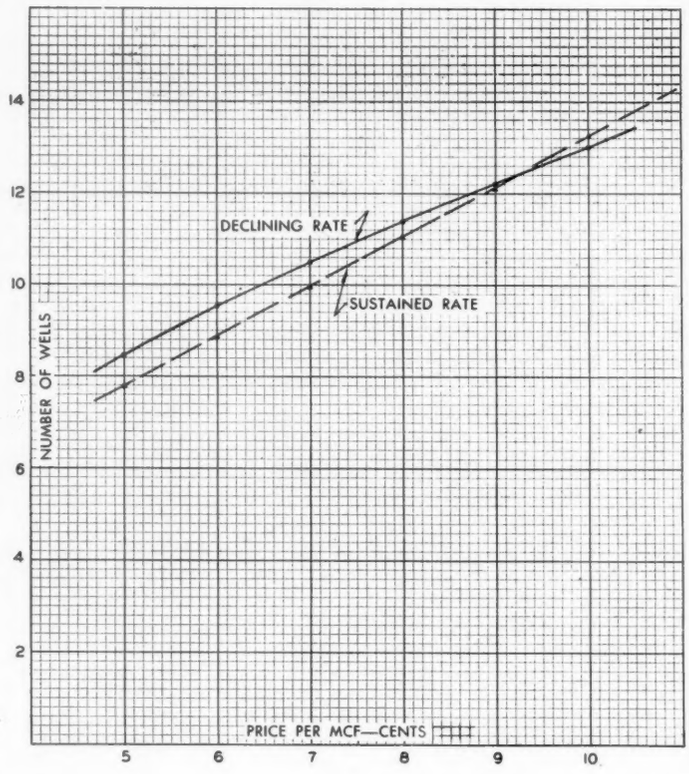


FIG. 3.

that the bases have not changed markedly. With such an observation a general solution to the well-spacing problem, showing at least the general variation of spacing with the major parameters, can be made under the following assumptions:

1. Flow in the reservoir is viscous and isothermal.
2. The gas obeys Boyles' law.
3. All wells are operated constantly at a back pressure equal to a constant fraction of the closed pressure.
4. The optimum spacing is defined as that spacing yielding the maximum net income to the producer.

Although none of these conditions is essential, they do permit a simple solution, and they do not differ markedly from actual practices.

The gas from these wells may be produced either at a constantly declining rate to produce a maximum income or at a constant rate to satisfy pipe-line requirements. The first is analytically simpler; but it is impractical, and results in a spacing not greatly different from the analytically more difficult one of sustained capacity.

Results shown in Figs. 1, 2, and 3 are based upon a field of the following constants:

Production area, acres	4,720
Net thickness, feet	20
Porosity, per cent	20
Interstitial water, per cent	30
Reservoir pressure, atmospheres	200
Reservoir temperature, deg F	200
Deviation factor	1.1
Reserve per acre (15 lb), MCF	21,200
Reserve for field, MMCF	100
Time on which income is calculated, years	10
Operating expenses, per well per year	$1,000

Variables are taken to be the price per 1000 cu ft, cost per well, and initial capacity per well. These are assigned certain basic values:

Price per MCF	$ 0.05
Cost per well	$100,000
Initial capacity per well, MCF per day	10,000

Certainly the most noteworthy point about the results is that the spacing is not greatly affected by considerable change in the variables. The calculated spacings are very similar to those used in actual practice. The economic factors involved in gas production have led to a spacing in general accord with theory.

Powerful!

More than five billion husky men working continually would be required to do the work done by U.S.-produced petroleum. On a 40-hour-week basis, almost 24 billion men would be needed to equal the power of petroleum.

The Analytical Solution

Under viscous, isothermal flow the capacity of J wells in a field will be:

$$C = J\phi(P_v^2 - P_\omega^2) \quad . \quad . \quad . \quad (1)$$

When: P_v and P_ω are the reservoir and working pressures. The amount of gas in the reservoir is proportional to the pressure. Then, as $\beta P_K = R_K$:

$$C = J\phi\beta^2(R_v^2 - R_\omega^2) \quad . \quad . \quad . \quad (2)$$

If each well is produced at a rate such that $P_\omega \propto P_v$,

Then:

$$\frac{dw}{dt} = J\phi\beta^2 a R_v^2 \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Where:

W is the cumulative withdrawal from the reservoir.

Therefore:

$$t = \frac{1}{J\phi\beta^2 a}\int_{o}^{W}\frac{dW}{(R_o - W)^2} \quad . \quad . \quad (4)$$

Where:

R_o = initial reserve.

$$W = R_o\left[1 - \frac{1}{1 + \frac{C_j j t}{R_o}}\right] \quad . \quad (5)$$

With a gross income of ψW. a cost per well of Φ, and annual operating expense of θ:

$$I = \psi W - J(\Phi + \theta t) \quad . \quad . \quad . \quad (6)$$

$$I = \psi R_o\left[1 - \frac{1}{1 + \frac{C_j j t}{R_o}}\right] - J(\Phi + \theta t)$$

$$. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The maximum value of I is obtained by differentiating equation (7) with respect to J and equating to zero:

$$J_{max} = \frac{R_o}{C_j t}\left[\left(\frac{\psi C_j t}{\Phi + \theta t}\right)^{1/2} - 1\right] \quad (8)$$

If the capacity is to be maintained for t years at a constant value, the income equation and the well spacing become:

$$I = \psi C_j J_o t - \Phi J_o\left[\frac{1}{1 - \frac{C_j J_o t}{R_o}}\right]^2 - \frac{\theta R_o}{C_j}\left[\left(\frac{1}{1 - \frac{C_j J_o t}{R_o}}\right) - 1\right] \quad . \quad . \quad (9)$$

$$\psi C_j t = \frac{\Phi + \theta t}{\left(1 - \frac{C_j J_o t}{R_o}\right)^2} + \frac{2\Phi\frac{C_j J_o t}{R_o}}{\left(1 - \frac{C_j J_o t}{R_o}\right)^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Where:

C_j = initial well capacity.

J_o = intial number of wells.

List of Symbols

C = capacity, MCF per day.

C_j = capacity per well, MCF per day.

J = number of wells.

$\phi = \dfrac{\delta\pi\gamma\kappa}{\mu \log \dfrac{V_v}{V_\omega}}$.

δ = constant.

P_v = reservoir pressure.

P_ω = working pressure at well bore.

β = constant of proportionality $= [A\gamma f(1-s)]^{-1}$.

A = area of reservoir, square feet.

γ = sand thickness.

f = porosity.

s = interstitial water.

R = reserve.

W = withdrawal from reservoirs.

t = time.

ψ = price per MCF at well.

Φ = investment per well.

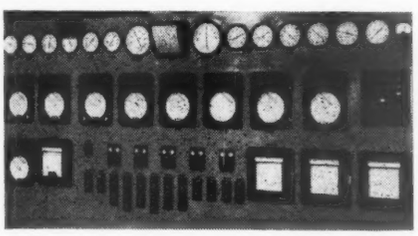
θ = annual operating expense per well.

I = net income.

v = as subscript, reservoir.

ω = as subscript, well.

$_o$ = as subscript, initial. ★ ★ ★



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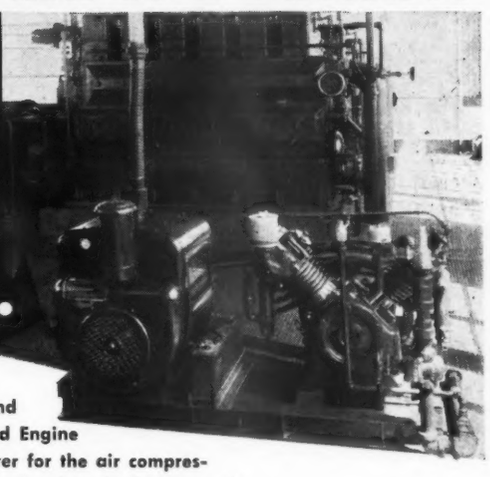

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Procedures, Benefits, and Problems of Unitization

C. B. CARUTHERS*

UNITIZATION is becoming more and more important in oil operations. For example, my company entered its first unit in 1930. During the next ten years we became a party to two more unit agreements. In the last nine years, however, we have joined in thirty-five additional units. I believe our increased interest in units is somewhat representative of the trend in the industry. As more and more oil producers and royalty owners realize the increased oil recoveries possible by unit operations, this trend should accelerate. I am going to discuss the overall subject of unitization in a general way. At the end of my talk, we can discuss any features of particular interest to you.

Definition of Unitization

I define unitization as: *the act of combining separately owned interests and rights in certain lands and leases in a way that will allow development and production without regard to lease or property lines.* A unit may cover everything from the surface down. On the other hand, it is possible to limit a unit to only oil or gas produced from specific formations. Sometimes operating arrangements between owners of working interest only are called units, but for this discussion I will talk only about those which involve both the royalty and working interest.

Types of Unitization

As I see it there are only two general types of units. The first is the *spacing unit,* where small leases or undivided interests are combined to form an area conforming to the established spacing pattern for the field. These small units are formed for the purpose of drilling and producing only one well. The second is the *fieldwide* unit where separately owned interests in the productive area of one or more reservoirs are integrated. Although spacing units are of great importance and essential in oil and gas operations, the larger fieldwide units are of the most importance. Comments on fieldwide units apply in a general way to spacing units since the primary purposes of both are the same.

Basic Purposes of Unitization

The basic purposes of any unitization are:

1. To minimize waste,
2. To increase ultimate recovery, and
3. To protect the correlative rights of the owners in the common reservoir; that is, the right of each owner to produce or receive his just and equitable share of the production from the reservoir.

If these basic purposes can be accomplished to a maximum under ordinary lease operations then there is no justification for the formation of a unit. I believe that accomplishment of these three purposes will meet the fundamental requirements of any state or federal unitization law or regulation. Some of you may be wondering about the profit angle. As a practical matter, the program to be conducted must be economically feasible if it is to be given serious consideration.

Methods of Unitization

There are two general ways of forming a unit. One, commonly referred to as *voluntary,* is by mutual consent of all or a substantial majority of the interested parties. The other, sometimes called *compulsory,* is by the application of state statutes where available.

Under the voluntary method, a unitization agreement is circulated for signature of the royalty and working interest owners. The unitization agreement is filed of record as notice to the public that the unit has been formed. Some leases give the working interest owner the option of forming a unit at his election. In such cases the working interest owners may file a declaration of record, and thereby form the unit without further consulting the royalty owners. It is only in rare instances that the lease grants the right to form a unit of an area larger than a spacing unit, so unitization agreements are almost always required when forming voluntary fieldwide units.

State Laws

Where fieldwide units are formed by the application of state laws, the procedure set out in the statutes governs. Ordinarily, the unit becomes effective after proper application, notice, public hearing, and finding of the state regulatory body involved that the plan is a proper one. The statutes in some instances provide for the minimum percentage of ownership that must approve the plan before it will be considered. In other states these requirements are left solely to the discretion of the regulatory body in charge. The states of Alabama, Florida, Georgia, and Oklahoma have so called compulsory unitization laws applicable to fieldwide units and covering both oil and gas. Louisiana has a statute which provides for compulsory unitization of gas pools for cycling purposes. The state regulatory bodies in Arizona and Illinois can compel the unitization of state lands. Several other states, including Arkansas, Michigan, Mississippi, and New Mexico have compulsory unitization laws applicable to spacing units.

The Oklahoma fieldwide statutes along this line have probably received more publicity than those of any other state. In Oklahoma, the owners of 50 per cent or more of the working interest in the area proposed for unitization, computed on a surface acreage basis, must join in the initial application to the Corporation Commission for a unit plan of operation. If the Corporation Commission finds that the plan is fair and proper, it will issue an order approving the plan. This order becomes effective within 60 days, unless owners of 15 per cent or more of the working interest file a written protest. Written protest by 15 per cent or more will vacate the order of the Corporation Commission. If the order is not protested and becomes effective, all working interests and all royalty interests in the unit area are unitized. You will note that the unusual feature of this procedure is that it is not necessary for the royalty owners to sign anything approving the unit; however, the royalty owners and all other interested parties do have ample opportunity to appear at the public hearing held by the commission on the application and to support or oppose the application as they see fit.

Louisiana Procedures

On the other hand, in Louisiana, the commissioner is authorized, after notice and upon hearing, to determine

*Unitization Superintendent, Stanolind Oil and Gas Company, Tulsa, Oklahoma, who presented this paper to the Mississippi Landmen's Association in Jackson, Mississippi, on May 9, 1949.

the feasibility of a fieldwide unit covering gas cycling operations. This would seem to authorize the commissioner to proceed on his own motion in a proper case without the need of obtaining the consent of either working interest or royalty interest owners. However, in practically all instances, the consent of the majority of the working and royalty interest owners has been obtained prior to the filing of an application for a fieldwide unit covering gas cycling operations in Louisiana.

In your work you have probably heard some very good arguments both for and against compulsory unitization. My over-all feeling on the subject is that before a unit is formed by application of state statutes, a substantial percentage of the royalty and working interest owners should be in favor of the plan. On the other hand, owners of a minority interest should not be allowed to block a unit agreement that (beyond a reasonable doubt) will increase recoveries, promote conservation and protect the rights of all parties involved. There is a definite need in most oil-producing states for compulsory fieldwide unitization statutes. There is no doubt in my mind that many additional units of a highly desirable nature would be in operation today if adequate statutes were on the books.

The Federal government has been a strong advocate of unitization of federal lands since the early 30's. Since that time, some 275 units involving federal lands have been approved by the Secretary of Interior. Many valuable deposits of oil and gas have been discovered and are being developed within these units.

General Procedure

Here are some of the fundamental steps in building a fieldwide unit:

1. All of the geological and engineering information on the area must be analyzed thoroughly. If this analysis shows waste can be minimized, ultimate recovery can be increased, and correlative rights can be protected directly or indirectly as the result of unitization, then unitization should be attempted.

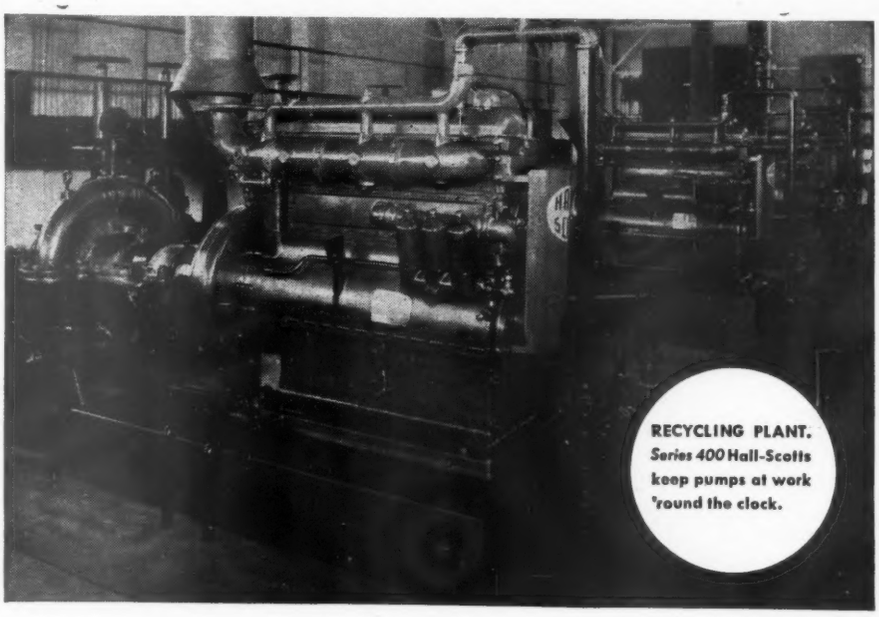
2. Having decided to unitize, the applicable state and federal laws, rules, and regulations must be examined. This examination will reveal the type of plan and form of application required. In this connection, you should remember that the Department of Interior has rather specific and detailed rules and regulations where federal lands are involved.

3. Working interest owners then must agree on these things:

a. The area to be included, usually referred to as the unit area.
b. The formations and substances to be unitized.
c. The designation of a unit operator.
d. The powers of the unit operator.
e. Method of controlling operation of the unit and actions of the unit operator.
f. Method of allocating unitized substances.
g. The manner in which costs and expenses are to be borne.
h. How investment in existing wells, equipment and facilities will be adjusted.
i. The method of handling title examinations.
j. The accounting procedure which is to govern.
k. How the unit area is to be enlarged or contracted.
l. The term or life of the unit.
m. Any other questions peculiar to the project.

4. Agreements incorporating all of the legal and operating features to the satisfaction of all parties and interests must be prepared.

5. The agreements must be ap-



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proved by sufficient parties and regulatory agencies to permit effective unit operations in accordance with the terms of the agreements.

Unitization Benefits

We should now consider some of the benefits possible as the result of unitization:

1. Any proper plan of unitization is definitely in the public interest. Petroleum is an exhaustible natural resource and each barrel of additional oil recovered, as the result of better operating practices possible with unitization, is the equivalent of a barrel of oil discovered. This is particularly significant because new reserves are becoming harder and harder to find. It is the duty of the oil operators to recover every possible barrel of oil from the sources now proved.

2. A proper unit plan will benefit the interested parties in some and possibly all of the following ways:

a. All development and operations within the unit area may be conducted without regard to lease and property lines which means that:

(1) Controlled pressure decline or secondary recovery programs involving the injection of water, gas or other extraneous fluids may be inaugurated so that substantial increases in ultimate recovery will result. This is considered the major advantage of unitization because many increased recovery projects are impractical or inefficient on a lease basis.

(2) Wells drilled after the effective date of a unit may be located at the most favorable structural positions where they will make a maximum contribution to ultimate recovery.

(3) The drilling of wells that will not contribute to the ultimate recovery may be eliminated.

(4) The natural energy contained in the reservoir may be used to the very best advantage. For example, wells which produce inefficiently because of high gas-oil or water-oil ratios may be shut-in and production taken from more efficient producers.

(5) Investment in lease and other surface equipment and operating expenses may be reduced by the consolidation of lease and other facilities and by having only one field organization. Another reduction in operating expenses may be accomplished by delaying or eliminating entirely the necessity for artificial lift equipment, as the result of maintaining reservoir pressure.

(6) Accounting costs of both the operator and non-operator are reduced by the use of a summary form billing covering the entire operation instead of handling the accounting for each separate lease in the unit.

b. Usually all oil and gas is collected and utilized either through sales or by injection to the end that maximum economic return is realized by all parties. This means that wasteful practices, such as gas flaring, may be discontinued.

c. In some states gas-oil ratio penalties may be eliminated or greatly reduced by injecting the casinghead gas back into the reservoir. This results in higher allowables and allows the oil to be recovered in a more efficient manner. In certain states, particularly in Texas, injection of gas may prevent oil properties from being shut down entirely. I assume that gas injection would not be feasible on a lease basis, so credit these benefits to unitization.

d. Cycling of wet gas reservoirs, not usually feasible without unitization, results in recovery of the liquid hydrocarbons in a more efficient manner and usually at an increased rate. In cases where there is a possibility that some of the liquids would drop out in the reservoir and become unrecoverable if the pressures were allowed to decline, the increased recovery as the result of maintaining pressure may be appreciable.

e. The operation of a unit by one operator permits the assembling of complete geological and engineering information. This makes it possible to operate the unit much more efficiently than if each lease were operated on the basis of its lease information only.

f. Each working interest and royalty owner participates in production for the entire life of the unit, regardless of when the particular lease he contributed to the unit ceases to produce. This means that in addition to other benefits, each owner is assured of an income until the reservoir is depleted.

g. Certain additional advantages result from including federal lands in units. For example,

(1) Such lands are eliminated from acreage charges against their working interest owners.

(2) Term leases are perpetuated for the life of the unit.

(3) A new discovery, after the effective date of the unit, entitles the working interest owners to a straight 12½% royalty rate even though the federal lease may provide for a higher rate.

The royalty owners may contend that some of the above advantages benefit only the working interest owners; however, anything that benefits the working interest owners will, I feel, also benefit the royalty owners. The reason for this is that savings to the working interest owner will allow economic operations to a lower producing rate. This in turn will result in greater ultimate recovery and a greater total income to the royalty owner. Unitization should be particularly attractive to the royalty owner because he doesn't have to pay any of the additional costs. In other words, the working interest owners put up all of the money and take all of the chances. If the program is successful, the royalty owners get a share of the increased recovery. If the working interest owners make a mistake, it still doesn't cost the royalty owners anything.

Unitization Problems

You may say that the advantages of unitization sound all right, but what about some of the objections raised by royalty and working interest owners who are not sold on this method of operation. For this reason, I would like to mention some of the problems frequently encountered, and to attempt to give you some ideas to use in overcoming these problems:

1. A general lack of knowledge of the unit plan of operation is probably the largest single obstacle found. In other words, many working interest owners and a majority of the royalty owners just don't know what you are talking about. This situation prevails in spite of the fact that the theory of unitization was advanced some 35 years ago, and some unit projects have been in operation over 20 years. Overcoming this condition is the job of the people promoting a unit plan. If you are trying to unitize an area, you must take the time and trouble to develop a complete and simple explanation of what you are proposing and how it will affect everybody concerned. The landman, or whoever is to take the agreements around for signature, must understand the program well enough to explain it to those he will ask to sign.

2. One of the largest hurdles in negotiating a unit is the basis of participation. The basis of participation determines how each party will share in unit production. This is where "protection of correlative rights" comes into play. If the working interest owners can agree on participation they can usually agree on the other features without very much trouble. Difficulty

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in agreeing on participation will result if the negotiators assume a highly technical attitude. In other words, the negotiators must recognize the necessity of compromising various interpretations as to the relative value of tracts before progress can be made. In some cases, a negotiator will use the fact that his properties are essential to the success of the program in an effort to obtain a participation greater than that to which he is entitled. Such an attitude may prevent the honest approach to participation that is necessary. The working interest owners must never lose sight of the fact that the interest (correlative rights) of each royalty owner must likewise be protected in unit negotiations. About the only solution to these problems of participation is to try to prevail upon the negotiators to be fair and open-minded in solving the problem.

3. You sometimes encounter parties who are not necessarily against unitization, but who do not believe the method of operation to be followed under unitization will result in increased recoveries. This attitude usually represents an honest difference of opinion. The best means of showing the probable benefits of the proposed operation is to show the results of a similar program which has proved successful in a comparable field. If information of this type is not available, it is necessary to rely on theoretical reservoir calculations. Both high and low pressure injection projects are becoming more numerous and it shouldn't be long before we can point to successful projects in nearly all areas.

4. Some states have either inadequate or no unitization laws, which sometimes provides a serious obstacle to unitization. For example, Texas' statutes are silent on unitization for oil, except that state lands may not be so unitized. This simply means that unitization of state lands in Texas for the production of oil is out of the question.* Without going into detail it is considered sufficient to say that with 3 or 4 exceptions, state statutes regarding unitization leave much to be desired. The problem of adequate state statutes is one for the respective legislative bodies to handle. It is encouraging to note that in most oil producing states, these bodies are making an effort to provide unitization laws. In Texas for example, the legislature now has under consideration the Moffett Unitization Bill, which if approved will adequately take care of this situation. Of considerable benefit along this line is the work being done by oil industry organizations such as the Section of Mineral Law of the American Bar Association and the Interstate Oil Compact Commission. Recognition is also due those state senators and representatives who recognize the problem and are attempting to do something about it.

5. You frequently hear working interest owners say they are afraid a unit organization will be classed as an association and thus taxable as a corporation. This objection can be overcome if the joint operating agreement is properly written. The Bureau of Internal Revenue has recently issued rulings on joint operating agreements (IT 3930 and IT 3933) regarding the association angle. These rulings, now being clarified and adopted, will make it possible to prepare joint operating agreements so as to practically eliminate any possibility of taxation as a corporation. Right now it appears that if each party has the right to take in kind and to individually market his share of unitized substances there is no danger of double taxation.

6. Working interest owners sometimes decline to join in a unit for fear that damages will be awarded royalty or working interest owners who do not join. Such liabilities are definitely minimized if all parties are initially

*Editor's note: The Texas legislature passed a unitization measure in May, 1949.

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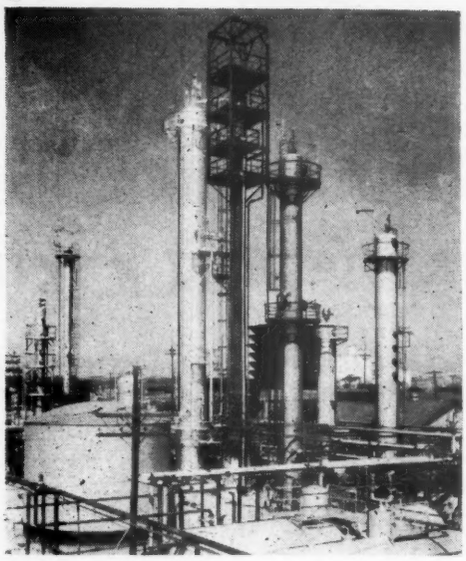

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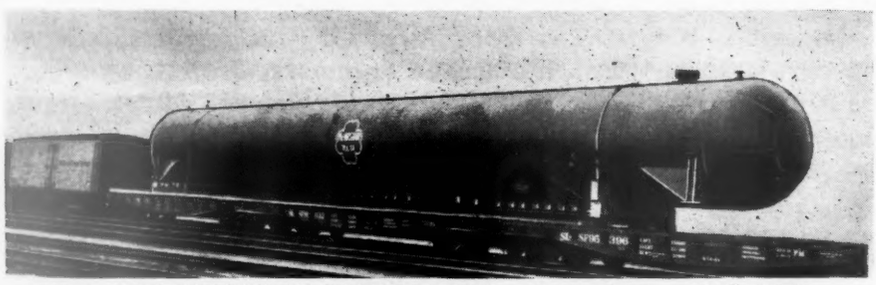

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offered an opportunity to join in the unit on a fair and equitable basis. Another protection is that in forming voluntary units it is necessary to get a very high percentage of all interest owners to join before the plan can operate efficiently. This leaves only a small percentage of unsigned interest owners and the possible liabilities are correspondingly small. It is the practice of practically all working interest owners to settle with their non-joining royalty owners on a lease basis. In those states where the statutes provide for compulsory unitization the possibility of such damages is further reduced.

7. Some working interest owners feel that they can operate their properties better than a unit operator could. This feeling can be overcome in some instances by letting that particular party operate the unit. If this arrangement isn't practical it is necessary to enumerate the many beneficial services the Unit Operator will render at a nominal cost. Examples of units operating successfully may also prove convincing.

8. Working interest owners occasionally question each others' motives. This is particularly true where one operator owns a substantial portion of the area to be unitized. In this situation the job of demonstrating the fairness of the plan falls to the working interest owner promoting the unit. Complete information presented in a clear and understandable manner will do much to eliminate suspicion. Actually there is no incentive for the promoting parties to withhold any pertinent information if the project is open and above board.

Future of Unitization

The theme of this discussion has been that the largest task facing us in future unitization efforts is one of education. It is a lot of trouble to explain how unitization works to the large number of parties ordinarily involved in an operation of this type. On the other hand, I believe the expected benefits in the form of increased recovery and the conservation of natural resources far out-weigh the work involved.

As mentioned earlier, it is with increased difficulty that new reserves are being found. It is not only the desire but the duty of oil operators to conserve and recover every possible barrel of oil which has already been discovered. I believe unitization not only can but will play an important role in achieving these goals.

By way of summary, it appears the rate of increase in the number of unit operations will depend primarily on (1) how fast working and royalty interest owners can be educated as to the advantages of units, (2) how successful the operations of completed units prove to be, and (3) the rapidity with which states adopt adequate unitization laws.

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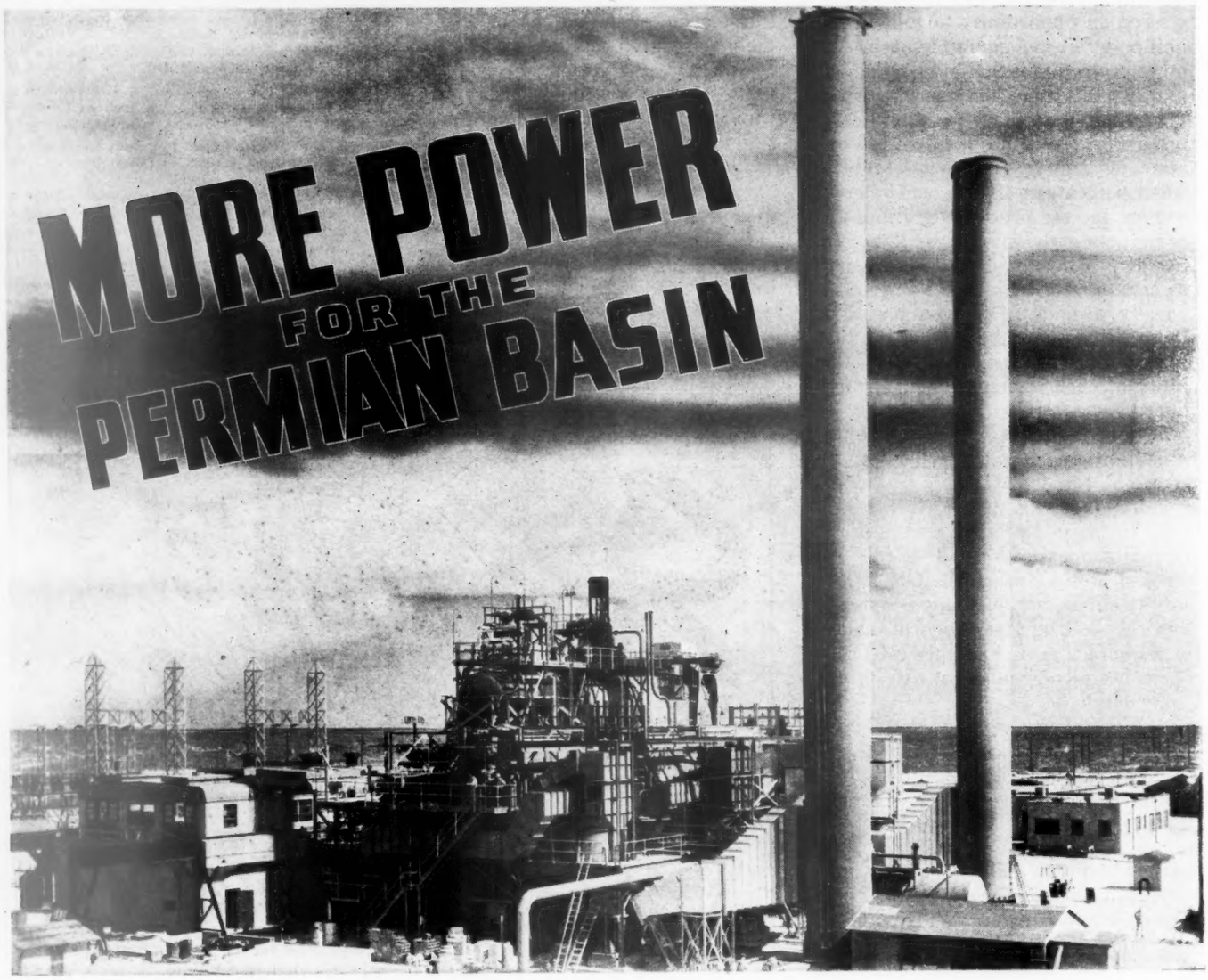

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Hydrafrac Process for Increasing the Productivity of Wells*

J. B. CLARK†

Abstract

The oil industry has long recognized the need for increasing well productivity. To meet this need, a process is being developed whereby the producing formation permeability is increased by hydraulically fracturing the formation.

The "Hydrafrac" process, as it is now being used, consists of two steps: (1) Injecting a viscous liquid containing a granular material, such as sand for a propping agent, under high hydraulic pressure to fracture the formation; (2) causing the viscous liquid to change from a high to a low viscosity so that it may be readily displaced from the formation.

To date the process has been used in 32 jobs on 23 wells in 7 fields, resulting in a sustained increase in production in 11 wells.

Need for Process

ALTHOUGH explosives, acidizing, and other methods have long been used, there still exists a need for artificial means of improving the productive ability of oil and gas wells, particularly for wells which produce from formations which do not react readily with acids. This paper discusses the development of a hydraulic fracturing process, "Hydrafrac," which shows distinct promise of increasing production rates from wells producing from any type of formation. The method is also considered applicable to gas and water injection wells, wells used for solution mining of salts and, with some modification, to water wells and sulphur wells.

Requirements of Process

In considering such a possible process, it appeared that certain requirements must be met. Some of these are as follows:

A. The hydraulic fluid selected must be sufficiently viscous that it can be injected into the well at a pressure high enough to cause fracturing.

B. The hydraulic fluid should carry in suspension a propping agent, such as sand, so that once a fracture is formed, it will be prevented from closing off, and the fracture created will remain to serve as a flow channel for oil and gas.

C. The fluid should be an oily one rather than a water-base fluid, because the latter would be harmful to many formations.

D. After the fracture is made, it is essential that the fracturing fluid be thin enough to flow back out of the well and not stay in place and plug the crack when it has formed.

E. Sufficient pump capacity must be available to inject the fluid faster than it will leak away into the porous rock formation.

F. In many instances, formation packers must be used to confine the fracture to the desired level, and to obtain the advantages of multiple fracturing.

Development of Process

As a necessary step in the development of this process, it was deemed advisable to determine if the Hydrafrac fluids were actually fracturing the formation, or whether these special fluids were merely leaking away into the surrounding formation. To determine this, a shallow well, 15 ft deep, was drilled into a hard sandstone. Casing was set, the plug drilled, and the well deepened in the conventional manner. A fracturing fluid dyed a bright red was used to break down the formation. Sand mixed with distinctively colored solids was injected into the well with the fracturing fluid to prop open any fracture made in the formation. A simulated gel breaker solution dyed a bright blue was then pumped into the well to determine if the gel breaker would follow the first solution.

The results are shown in Fig. 1. It was noted that a fracture was formed about the well bore, that the propping agent was transported back into the break, and that the breaker solution did actually follow the fracturing gel out into the fracture.

While it is realized that this shallow well test is probably not exactly equivalent to a deep test, the results were interpreted as being a definite indication of what happens down the hole during a Hydrafrac job.

Steps of the Hydrafrac Process

Fig. 2 shows a simplified cross-sectional view of a well treated by one version of the process. The first step, formation breakdown, is done with a viscous fluid, usually consisting of an oil such as crude oil or gasoline, to which has been added a bodying agent. Due to availability and price, war-surplus Napalm has been used in the majority of experiments to date. Napalm is the soap which was used in the war to make "jellied gasoline." The next step consists of breaking down the viscosity of the gel by injecting a gel-breaker solution and then after several hours, putting the well back on production. Fig. 3 shows diagrammatically, a typical field hook-up. The oil or gasoline is unloaded into the 10 bbl tank shown on the left rear of the truck. This base fluid is picked up by the mixing pump and pumped through the jet mixer, where the granular soap is added. Next it goes into a small mixing tub, from which the high-pressure pump takes suction. The solution is then pumped into the well. The breaker solution is then taken from an extra tank and is displaced into the well immediately following the gel. When required, additional trucks may be connected to the well so as to pump the fluids at a faster rate.

Planning the Field Job

The planning of a Hydrafrac job requires detailed consideration of the individual well conditions. Selection of the pumps and of the kind and amount of hydraulic fluid, for example, depends upon the thickness and permeability of exposed producing formation, the bottom hole formation pressure, the well depth, the pipe size and condition, and upon the weight,

*Presented before the Fall Meeting of the Petroleum Division, American Institute of Mining and Metallurgical Engineers, Dallas, Texas, October 4-5-6, 1948.

†Stanolind Oil and Gas Company, Tulsa, Oklahoma.

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APPEARANCES CAN BE DECEIVING

You don't judge a racing car on the floor of a display room. It may look sleek and powerful there, all right, but that isn't enough to convince you to place your bets on it. No, you judge a racing car during a race–during every lap of the race, but especially during the final, grueling sprint to the finish line.

You can't judge a casing centralizer on the derrick floor. It may look rugged and potentially effective there. But that's not where you center your casing. You judge a centralizer by its ability to deliver effective centering force to the bottom of the hole where its job must be done. At least, that's the way you'd *like* to be able to judge it. The rub is that you can't see what's going on at the bottom of the hole.

BUT THERE IS A WAY TO KNOW . . .

Yes, there is the Baker way – the scientific approach.

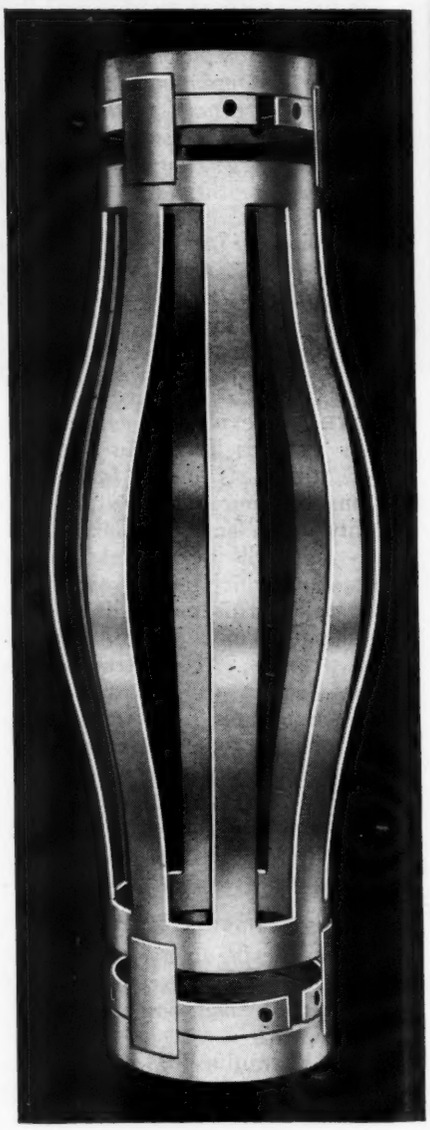
The test of a centralizer is its ability to exert maximum centering force AFTER the repeated flattening of its springs during the trip down-hole.

That's why our testing laboratory here at Baker has been kept in constant use during the design, development, and actual proving of our centralizer. Comprehensive tests, simulating every conceivable hole condition to which a centralizer is subject, were performed by Baker engineers in arriving at the unique design of the Baker Model "G" Casing Centralizer–*The* truly scientifically designed spring-type centralizer. During the course of these tests, every type of spring-type centralizer design was studied. The exclusive Baker Model "G" design proved convincingly to be the optimum.

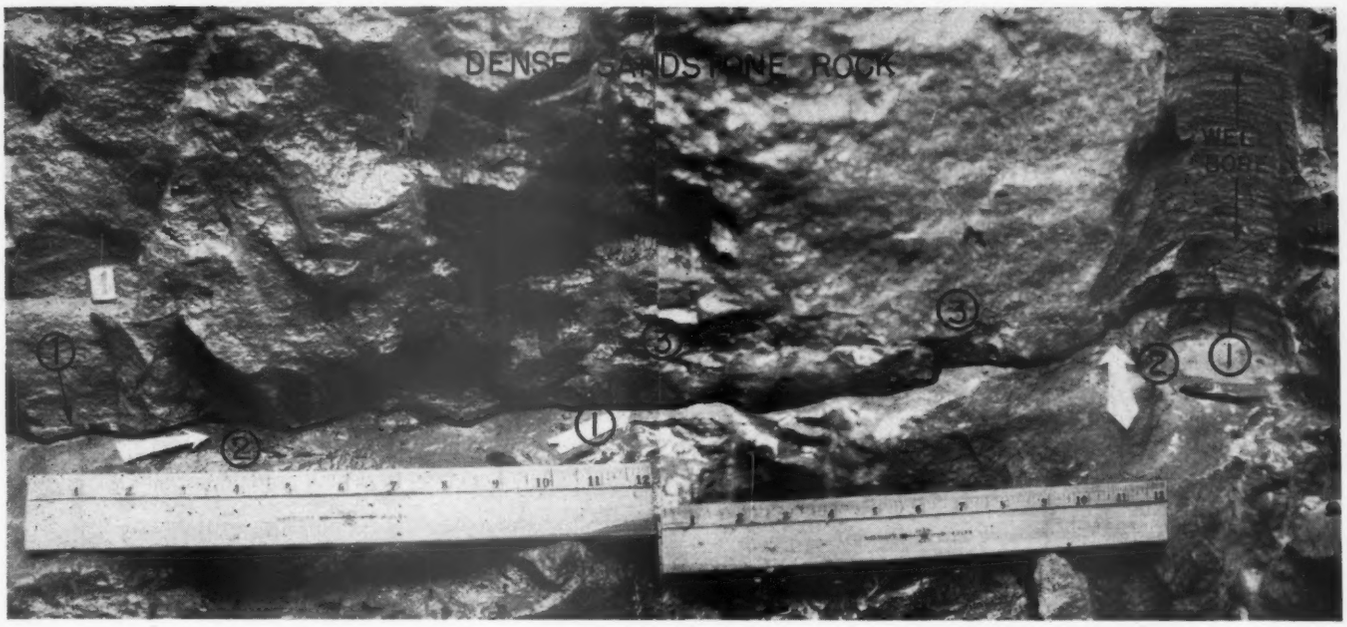
YOU CAN DEPEND UPON A BAKER CENTRALIZER

When you run a Baker Model "G" Casing Centralizer you can rest assured that it will do a proper centering job. As an operator, you need no longer worry about trial-and-error centering of your casing, because a Baker centralizer is a proven centralizer. Because of its design, the Baker Model "G" Casing Centralizer offers many exclusive advantages as well as desirable features.

1. It exerts maximum centering force where it is needed–not as the centralizer first enters the well bore or above the first well constriction, but after even the most rugged trip to the bottom of the hole where its actual centering job must be done.



Baker Model "G" Casing Centralizer, Product No. 910-G



1. FORMATION FRACTURE CONTAINING FRACTURING LIQUID.
2. EXPOSED FORMATION PROPPING AGENT.
3. ROCK ADJACENT FRACTURE PARTIALLY SATURATED WITH SIMULATED GEL BREAKER SOLUTION.

FIG. 1. Shallow well Hydrafrac job.

strength, and compressibility of the overburden.

Individual items that must be considered in the planning, and the method of meeting the detailed requirements for the fracturing fluid and equipment, are discussed in detail below, under the corresponding headings of hydraulic fluid requirements, pump requirements, and packer requirements.

Hydraulic Fluid Requirements

The usual hydraulic fluid requirement is for an oil phase material with viscosity between 50 and 150 centipoises or higher, depending on the individual job. It has been found that Napalm soap and similar soaps provide the desired characteristics. Napalm can be added to gasoline, kerosine, or other refined petroleum cuts to produce gels having any desired viscosity up to considerably over 300 centipoises.

Hydraulic Base Fluids. The ideal fluid should be an oily one rather than a water base fluid, to avoid decreasing the permeability of the formation to oil or gas. This requirement is met by the Napalm gel being used. Water base fluids, however, would be advantageous in treating water wells, or water injection wells used in either the oil industry or industries where water is used in solution mining of salts, and in the Frasch process of mining sulphur. There is also some reason to believe that a water base fluid could be used successfully in oil or gas wells. In other words, it is entirely possible that the benefits derived from hydraulically fracturing the formation may be great enough to overcome the decrease in permeability caused by water wetting of the oil or gas sand. It is known, for example, that limestone reservoirs can be acid-

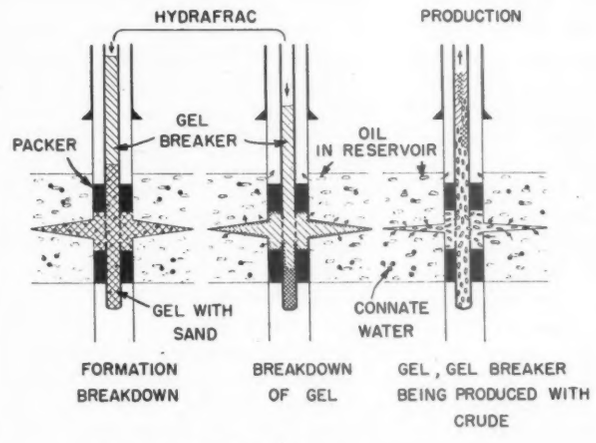


FIG. 2. Hydrafrac process.

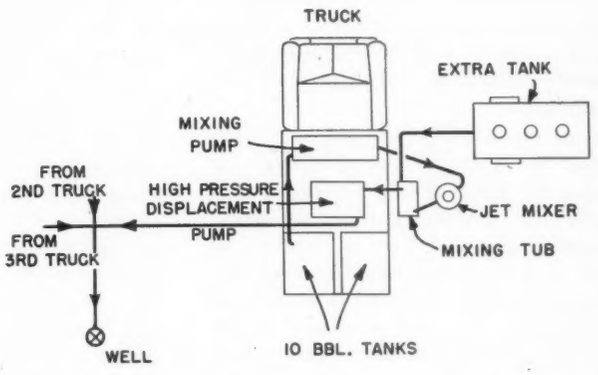


FIG. 3. Well hook-up using service company equipment.

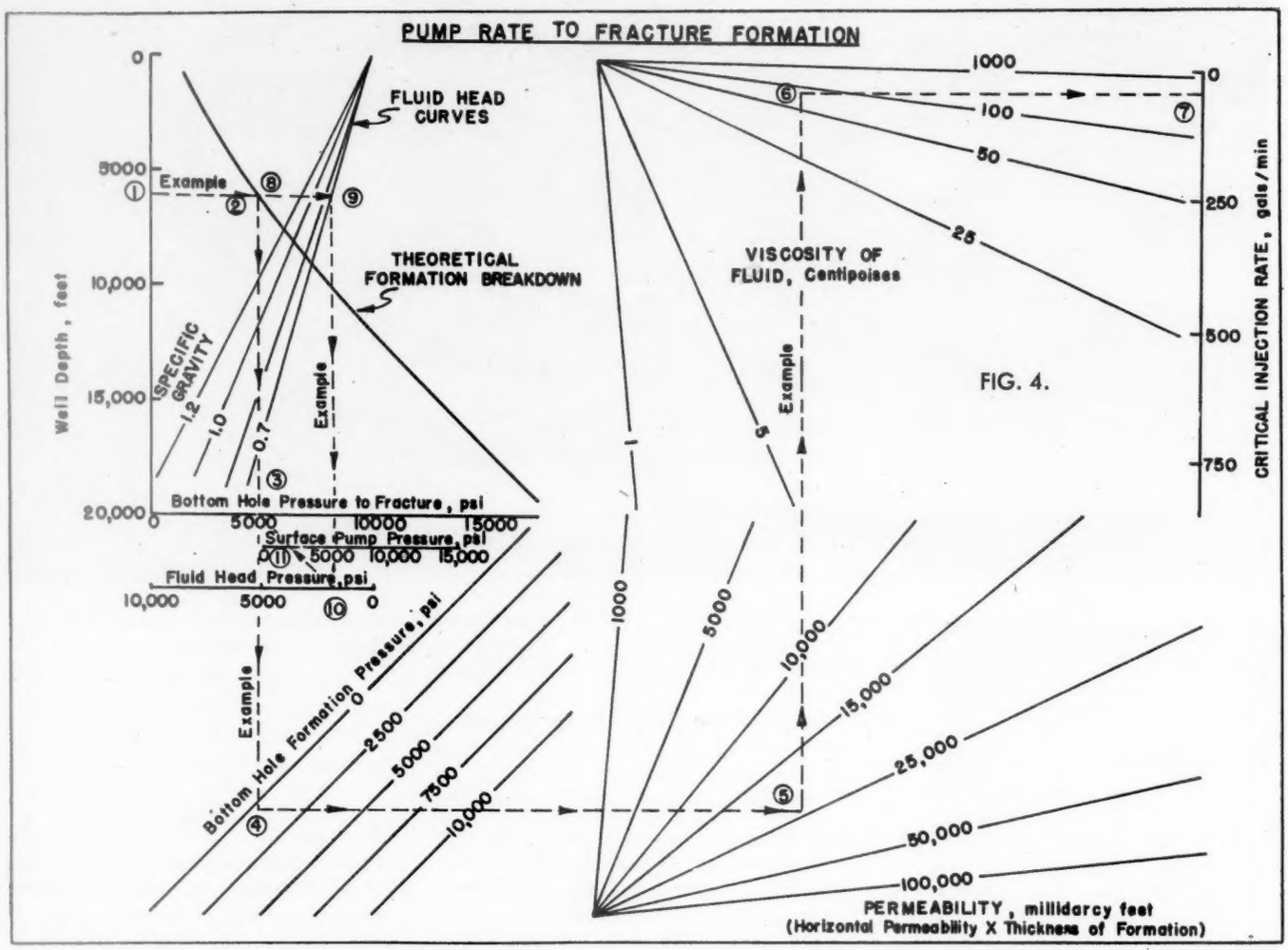


FIG. 4

FIG. 4

ized with an acid solution that is as high as 80 or 90 per cent water, with a resulting increase in well productivity. Future work with this process may indicate that is is more economical to use a water base for the hydraulic fracturing fluids than the more expensive gasoline and crude oil base fluids, particularly in formations not appreciably contaminated with argillaceous materials.

Sand Carrying Capacity of the Fliud. It is often desirable that the hydraulic fluid should carry in suspension a sufficient amount of strong granular material such as sand to be used as a propping agent to keep the fracture from closing off after release of pressure. The high viscosity of the Napalm gels makes them well suited to transport such material.

Breaking of the Fracturing Fluid Viscosity. After the fracture is made, the fracturing fluid must be thin enough to flow back out of the well. The Napalm gels have the advantage of being relatively unstable, so that the viscosity of the solution will revert to approximately that of the base oil after the fracture is formed.

A further advantage of the Napalm gel is that its time of reversion to a sol is controllable within definite limits. For example, it has been found that ½ per cent to 1 per cent of water added to a Napalm-gasoline gel will cause reversion to a sol within 8 to 24 hr, which gives ample time for performing the Hydrafrac job. Napalm-gasoline gels will revert to sols within an hour or two if they are in quiescent contact with either salt water or many types of crudes. Furthermore, it is also possible to use solutions which will break these gels in a few minutes under quiescent contact conditions. One example is a 2 per cent solution of petroleum sulphonates in gasoline or crude oil. This allows one to follow the Napalm gel with a second solution to insure its more rapid reversion to the sol condition.

Pump Requirements

Starting with well depth, fluid viscosity, formation thickness, and permeability and bottom hole pressure, it is possible to compute with fair accuracy, the pump rate necessary to fracture a formation and to extend the fracture after it is first made. Fig. 4 and 5 enable rapid determination of (1) pump capacity required to fracture a formation and to extend the fracture in the formation and (2), the necessary fluid viscosity to fracture and to extend the fracture in the formation with a given pump rate. These charts are based on a number of assumptions which would seem to oversimplify the computations, but nevertheless they have been found to be reasonably accurate in practice.

Field experience has shown that the successful Hydrafrac treatment requires a definite fracturing of the formation, as indicated by a decrease in injection pressure. This decrease in pressure is clearly shown on several

TABLE 1. Calculated vs. actual formation breakdown pressures.

Field	Well	Bottom hole pressure (psi) Calculated	Actual
East Texas	GA	3000	3350
Rangely, Colorado	EF	4800	4900
Hugoton, Kansas	AA	2500	2000
East Sasakwa, Oklahoma	FA	2600	2400
Frannie, Wyoming	BB	2700	2750

of the following charts. Table I, below, compares calculated breakdown pressures with those observed in the field. A comparison of the data presented in this table indicates a close agreement between the two figures.

Table 2 illustrates typical results of such computations made using data from Fig. 4 and 5. It is apparent from this table that, in formations of normal permeability, it is impossible to employ a fluid of high penetrating ability, such as the usual low-viscosity crude oil, for fracturing or extending the fracture. On sands such as in the East Texas Field, it would require a

TABLE 2.

Pump rate to fracture hydraulically.

	East Sasakwa field Booch sand	Hugoton field Ft. Riley lime	East Texas field Woodbine sand
Amount of open hole	35 ft	35 ft	20 ft
Average formation permeability	150 md	13 md	2000 md
Bbl/min to fracture			
Crude oil–5 centipoises	2	.13	21
Gel–100 centipoises	0.1	.007	1
Bbl/min to extend fracture to 50 ft radius			
Crude oil–5 centipoises	11	1	213
Gel–100 centipoises	0.6	0.05	10.7
Pressure to fracture	2100* 1250**	1700* 900**	2900* 1700**
Pressure to extend fracture	1700* 850**	1350* 550**	2600* 1400**

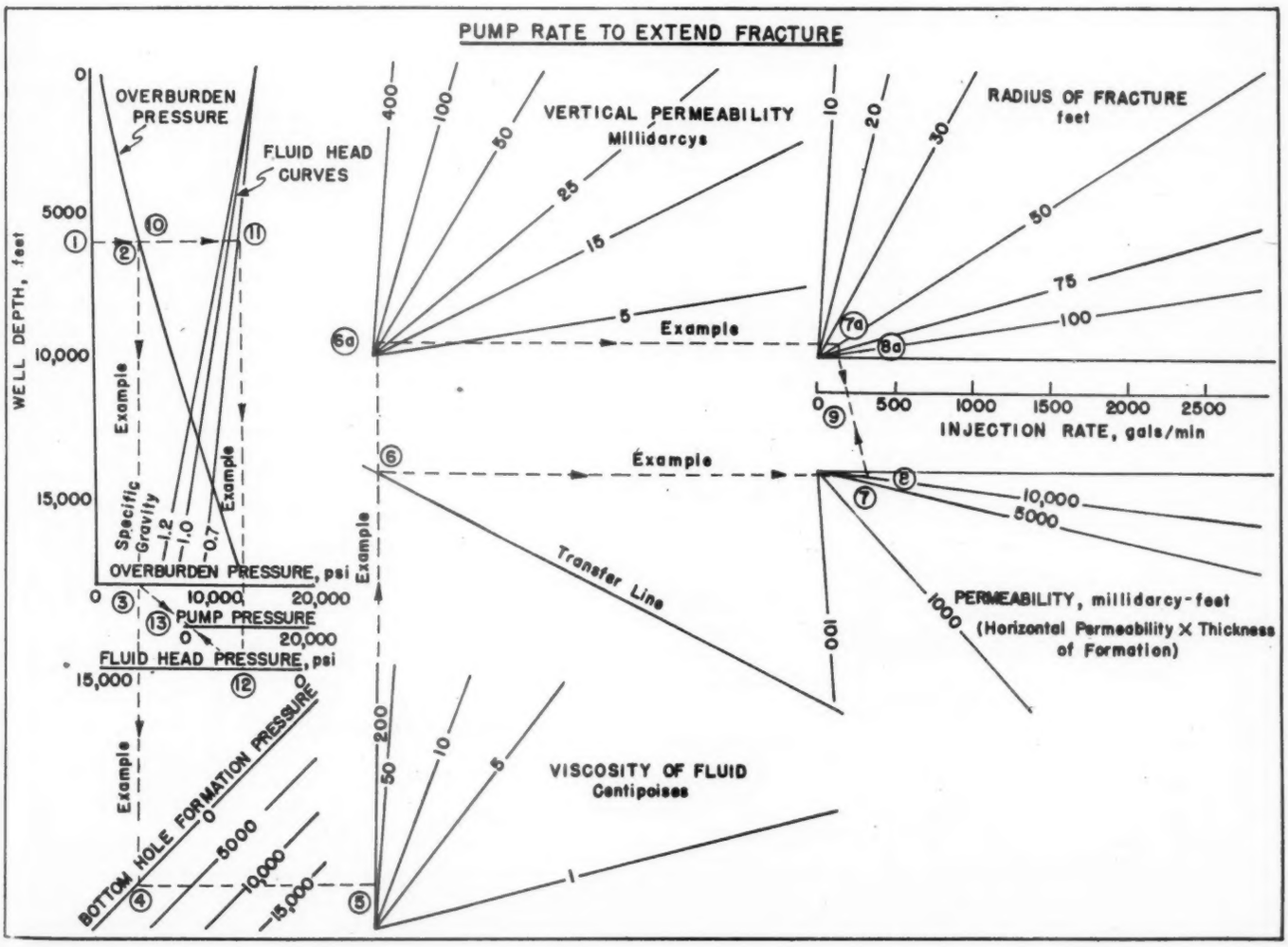
*Bottom hole pressure (psi).
**Surface pressure (psi).

crude oil injection rate of 21 bbl per min at approximately 2000 psi in order to fracture the formation, which is beyond practical limits, since the largest portable oilfield pumps deliver only about 3 bbl per min at this pressure. However, it is obvious from Fig. 3 that by using a higher viscosity material such as a 100 centipoise gel, the pump requirements are dropped to within practical limits both for fracturing and for extending the fracture.

Packer Requirements

In wells where the exposed sand section is quite thick, special precautions must be taken so that the hydraulic fracturing operation can be performed at more than one depth. Ordinarily, the formation will fracture but once, and the relative increase in production due to this single fracture might be negligible in a well having a large amount of productive sand thickness. To obtain the benefits of multiple fracturing, it is necessary to set special formation packers against the wall of the hole so as to isolate sections of a few feet in thickness before applying the Hydrafrac process. This technique is also important where it is necessary to prevent the fracturing fluids from

FIG. 5



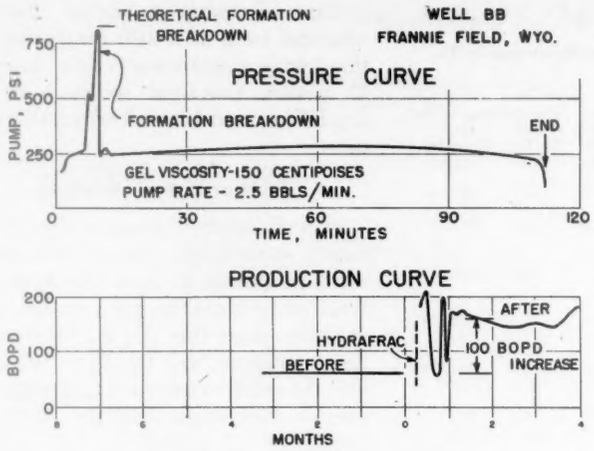


FIG. 6.

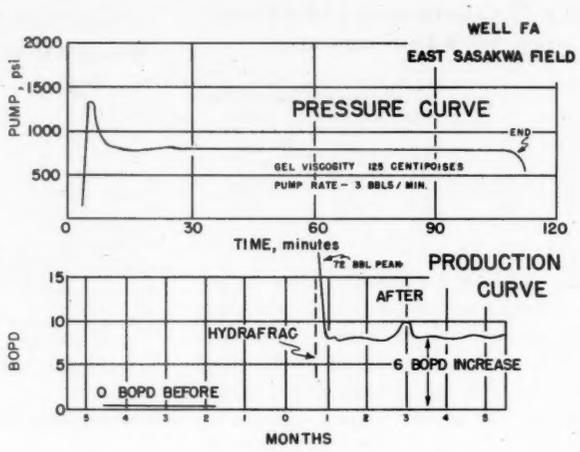


FIG. 7.

entering non-productive formations which may alternate with the producing zones exposed to the well. Packers are also required in some instances to keep the high pressures of the process from injuring pipe. Inflatable packers have been found best for this work, but due to the fact that such packers are still in the development stage, considerable mechanical difficulty has been experienced with them.

Hazards

The Hydrafrac process is accompanied by a considerable hazard to personnel. The materials usually used are inflammable and explosive, and this, together with the use of internal combustion engines, makes this process rather hazardous. It is believed, however, by exercising due caution such as covering mixing tubs and piping off engine exhausts that this process need not be more hazardous than the handling of any other inflammable liquid. The treating solutions have not ignited on any of the jobs done to date.

Wells Showing Sustained Increases in Production

The experimental application of the Hydrafrac process to oil and gas wells has resulted in sustained and significant increases in productivity on 11 wells out of the 23 in which it has been tried. A compilation of some of the key data obtained on these wells is shown in Table 3.

Six of these 11 successes are gas wells in the Hugoton Field; in one instance, a combination Hydrafrac-acid job was done, resulting in increasing deliverability from 53 to 439 MCF per day*, an increase from 53 to 322 MCF per day was the result of the Hydrafrac treatment, with a further increase to 439 MCF per day being the result of the subsequent acid job. On a Hydrafrac treated well, the deliverability was increased from 0 to 258 MCF per day, where the average of the offset wells completed by acidization indicated an increase in deliverability from 0 to 230 MCF per day. It is not possible at this time to make a complete evaluation of the advantages or disadvantages of a Hydrafrac-acid job or of a Hydrafrac job, over an acid job alone, but a program of comparison is in progress which will involve a sufficient number of wells to arrive at a definite answer.

*MCF per day = 1000 cu ft per day.

A much stronger case for the economic possibilities of the process is found in the five oil wells in which Hydrafrac has resulted in sustained production increases. These are as follows:

Frannie Field, Wyoming. Well BB increased from 60 to approximately 160 bbl per day and the Well BC from 60 to 72 bbl per day as the result of Hydrafrac treatment; both these increases have been sustained for over a year.

East Sasakwa Field, Oklahoma. Well FA in this field, which was producing no oil and was to be abandoned, has produced from five to six barrels per day for nine months since Hydrafrac treatment.

FIG. 8.

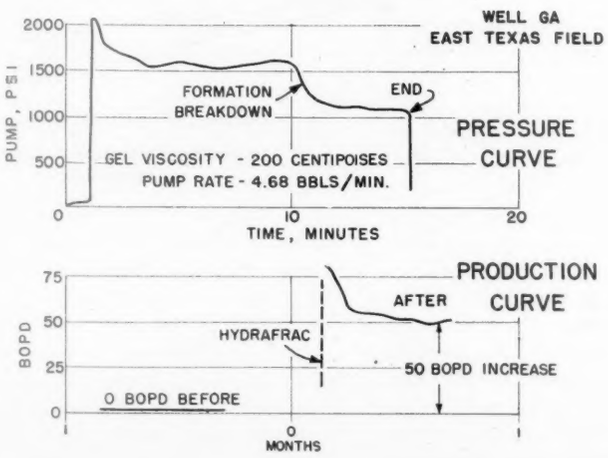
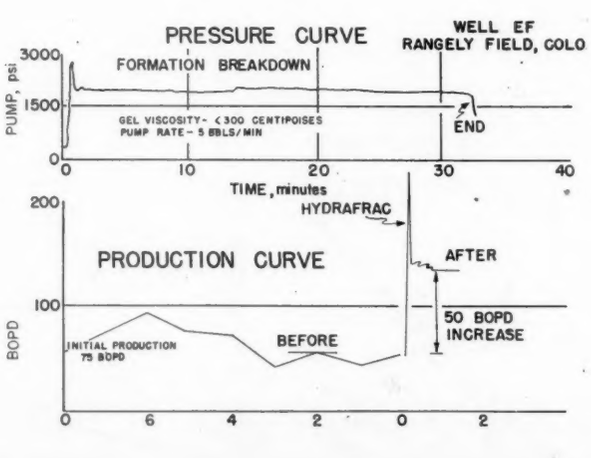


FIG. 9.



East Texas Field. Well GA which had produced no oil for two years produced more than 50 bbl of oil per day for several weeks while under special test after a Hydrafrac treatment, before being returned to its 20 bbl per day allowable rate. This well has been producing at the 20 bbl per day rate for five months since then, with periodic productivity tests to determine the maximum potential of the well. The last special test of this type indicated a well potential of 61 bbl of oil per day.

Rangely Field, Colorado. Well EF which was producing approximately 75 bbl of oil per day before treatment, is now producing approximately 140 bbl of oil per day as the result of Hydrafrac treatments.

Figs. 6, 7, 8, and 9 show for four of the above wells, the production curve before and after treatment, and the pressure curve taken during the Hydrafrac job showing the formation breakdown.

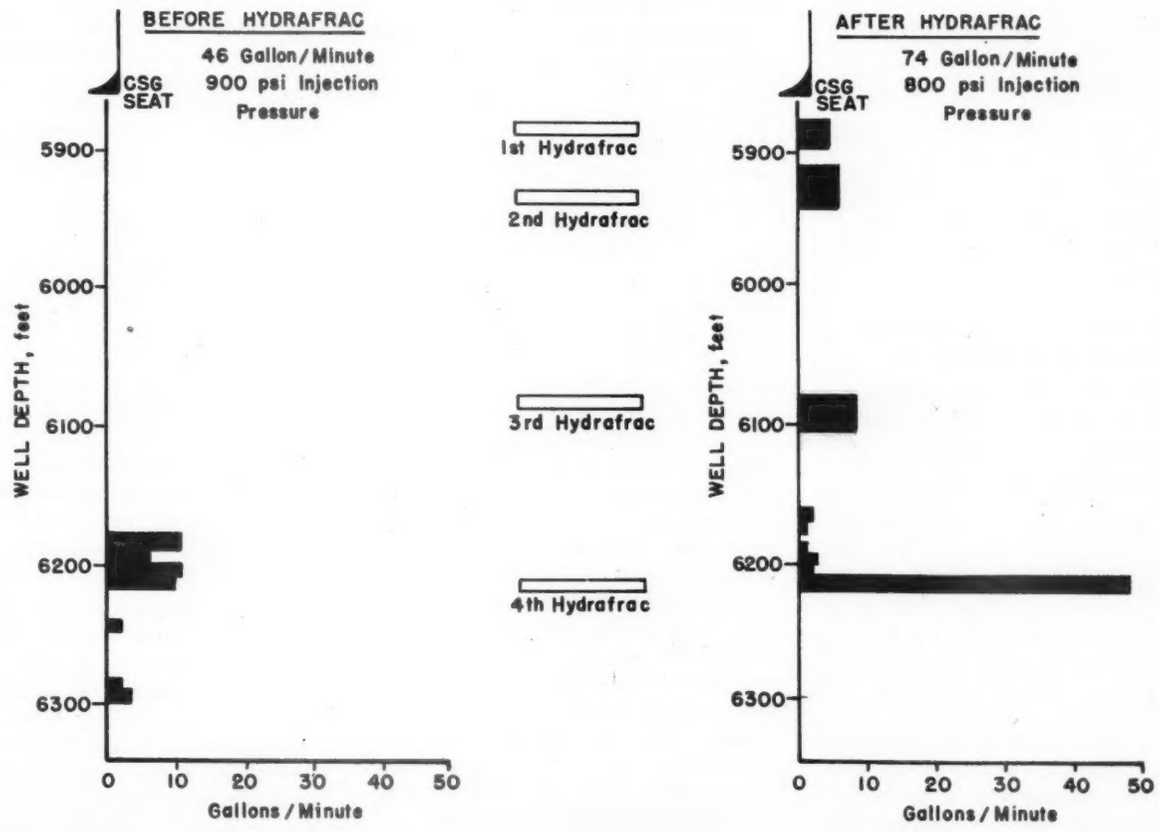
The effect on the permeability of selectively fracturing the producing formation of Well EF, Rangely Field, Colorado, is shown in Fig. 10 by a comparison of permeability profiles

TABLE 3. Results of hydrafrac field tests.

Field, Well	Formation Breakdown	Sand Injection	Production Before	Production After	Increase	Percent Increase
Hugoton (Gas) field, Kansas (A)						
Well AA	Yes	No	769 MCF	1015 MCF	254 MCF	33*
Well AB+	Yes	Yes	53	322	269	508
Well AC+	Yes	Yes	0	258	258	Infinite
Well AD+	Yes	Yes	0	322	322	Infinite
Well AE+	Yes	Yes	0	**	...	...
Well AF+	Yes	Yes	0	**	...	...
Frannie, Wyoming (B)						
Well BA	Yes	Yes	27 BOPD	27 BOPD	0 BOPD	0
Well BB	Yes	Yes	60	160	100	167
Well BC	Yes	No	60	72	12	20
Well BD	Yes	No	65	65	0	0
Elk Basin, Wyoming (C)						
Well CA	No	Yes	0 BOPD	0 BOPD	0 BOPD	0
Winkleman Dome, Wyoming (D)						
Well DA	No	Yes	91 BOPD	91 BOPD	0 BOPD	0
Rangely, Colorado (E)						
Well EA	No	Yes	100 BOPD	65 BOPD	—35 BOPD	—35
Well EB	No	Yes	100	100	0	0
Well EC	No	Yes	40	30	—10	—25
Well ED	No	Yes	106	100	—6	—3
Well EE	No	Yes	25	25	0	0
Well EF	Yes	Yes	75	140	55	73
East Sasakwa, Oklahoma (F)						
Well FA	Yes	Yes	0 BOPD	6 BOPD	6 BOPD	Infinite
East Texas (G)						
Well GA	Yes	Yes	0 BOPD	50 BOPD	50 BOPD	Infinite
Well GB	No	Yes	4	4	0	0
Well GC	Yes	Yes	8.25	8.25	0	0
Well GD	Yes	Yes	3.5	3.5	0	0

*Combined effect of Hydrafrac and acid.
+One of four producing zones treated.
**No post-Hydrafrac production this date.
MCF=1000 cubic feet per day.
BOPD=Barrels of oil per day.

FIG. 10. Permeability profiles indicating results of Hydrafrac treatments. Well EF, Rangely field, Colorado.



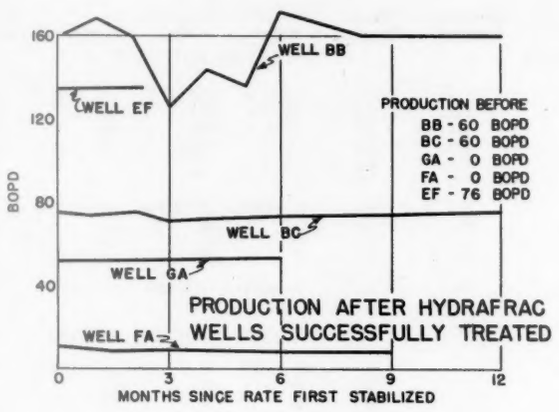


FIG. 11.

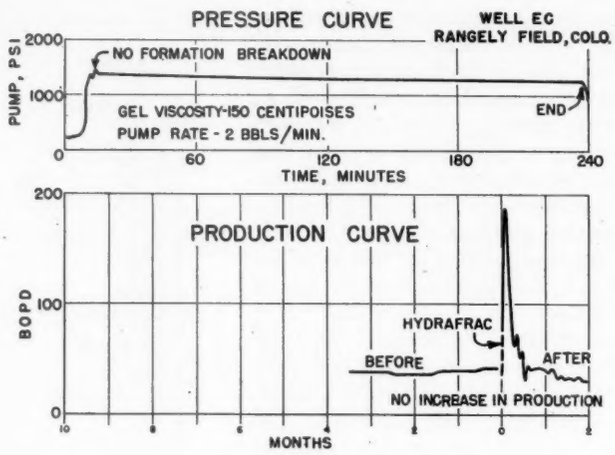


FIG. 12.

run before and after the Hydrafrac operation. The location of each Hydrafrac job is shown between the two permeability profiles. An effort was made to have the same injection pressure for both permeability profile tests, but pump capacity prevented obtaining as high an injection pressure after Hydrafrac as was obtained before. Some of the permeable zones indicated on the "Before Hydrafrac Permeability Profile" are not evident on the "After Hydrafrac Permeability Profile" due to the lower injection pressure. However, the increase in the permeability of those sections treated as the result of hydraulically fracturing the formation is clearly evident in this figure.

Figure 11 shows the production after Hydrafrac for these four oil wells successfully treated by this process. It will be noted in all instances that a sustained increase in production was accomplished by Hydrafrac.

Wells Showing No Sustained Increase in Production

No increase in production was obtained in 12 of the 23 wells treated in the preliminary experimental program. Considering the many variables involved, and the imperfections of present special packers, the proportion of failures at this stage of development is not discouraging. Both theory and field experience show that it is necessary to obtain a definite formation breakdown in order for the process to function satisfactorily. Fig. 12 shows the pressure curve and the production curve of Well EC, Rangely Field, Colorado, in which the formation did not breakdown and, as expected, no increase in production was obtained.

A comparison of Well EF and Well EC in the Rangely, Colorado Field illustrates the need for the proper isolation of the desired zones to be treated. It was possible on Well EF with suitable formation packers to confine the Hydrafrac fluids to the desired zones thus fracturing the pay formation in the most prolific sections. However, on Well EC where the Hydrafrac operations were attempted without the benefit of packers, the hydraulic fracturing fluid was dispersed over the entire area of the open hole with a resulting failure to increase well production.

Production data on the 23 wells treated by Hydrafrac are shown in Table 3. It may be noted that the productivity of three of the wells treated in the Rangely Field seems to have been slightly decreased by the Hydrafrac treatment. This decrease in well production after treatment is believed to be a result of either well workovers before treatment, or normal production decline during the well testing period. For example, the pay zone in Well EA was charged with crude oil before Hydrafrac treatment during a cleanout of the hole while using crude oil as a drilling fluid, and sufficient time was not allowed for the well production to level off before the well test taken before Hydrafrac treatment. The decrease in production of Well ED after treatment represents the normal production decline for this well. Part of the production decrease of Well EC may be attributed to normal production decline, however, trouble occurred which it is believed accounted for the majority of this decrease.

Predictability of Results

If the engineering factors surrounding a proposed Hydrafrac job are known, experience has shown that correct prediction of success or failure of the job is usually possible. A careful review of the jobs done to date leads to the conclusion that, even with due regard to the fact that "hindsight is clearer than foresight," it would have been possible to predict correctly at least 75 per cent of the failures, and 95 per cent of the successes, had all of the present field experience been available before each of the jobs done. As a matter of fact, many of the failures were predicted as such, and the jobs purposely done in the face of unfavorable well conditions in order to obtain research data. Incidentally, one of the treatments done under such circumstances (Well FA) was successful in spite of predicted failure.

Cost

When put into routine commercial use, the cost should be not much more than the cost of an acid job of corresponding gallonage. Where crude oil from the lease can be used as the base fluid in the Hydrafrac process, it is quite probable that the cost will be less than that for acidizing.

It is significant that the value of the additional oil and gas produced to date through the benefits of this process has already amounted to approximately 95 per cent of the combined cost of research, development, and all field tests.

Acknowledgments

Acknowledgment is due R. F. Farris, C. R. Fast, G. C. Howard, and other members of the staff of the Stanolind Oil and Gas Company's research and producing departments for their part in the development of this process. Appreciation is expressed to the management of Stanolind Oil and Gas Company for permission to publish this paper. ***

West Burkburnett Water Flood Project*

H. K. HOLLAND, JR.†

A discussion is presented on the West Burkburnett Field Water Flood Project. The basic criteria for the evaluation of a water flood project is outlined. The results obtained to date on a pilot water flood project in the field and the use of this information in developing the water flood program for the field is reviewed. A description is given on drilling and completion practice.

The source and characteristics of the water used for injection is discussed. The water distributing system for the field and the use of protective coatings for preventing corrosion is discussed. The necessity for obtaining accurate data on water flood operations and cooperative water flooding with offset operators to increase efficiency and total recovery is stressed.

Introduction

RECOVERY of oil by water flooding is practiced more extensively in North Texas than in any other section of the state. The large number of "stripper wells" in the area has stimulated the development of water flood projects; however, the small size of many of the fields and the thin oil producing sands in most areas has presented numerous economic and technical problems.

The West Burkburnett Field is one of the larger shallow fields in North Texas and is located approximately two miles southwest of Burkburnett in the Red River Valley Land Sub-Division, Wichita County, Texas. The West Burkburnett Field is part of what was formerly known as the Old Burkburnett Field, but is a separate reservoir from the numerous producing sands originally designated as a part of the Old Burkburnett Field.

Reservoir

Geology—The tectonic elements which seem to have controlled the accumulation of oil in this area is the Red River uplift. This is described by some geologists as being a chain of dissected Cambro-Ordivician limestones and granite hills.

Most of the sands in this area are known by depth in the respective fields in which they are found. The sand found in the West Burkburnett Field from approximately 1600 ft to 1850 ft belongs to the Cisco series of Pennsylvanian age. The sand is designated by some geologists as the Gunsight sand.

The structure of the Gunsight sand in the area to be water flooded is lenticular. The major axis of the lense runs east and west, and the sand dips approximately 250 feet from the south to the north in the field. The sand is broken or interspersed with shale which is characteristic of many of the oil producing sands in North Texas. The sand lenses into shale on all sides of the field.

The limits of the field have been defined by the wells drilled during the original development. The field was originally drilled on approximately ten acre spacing; however, many of the inside locations were never drilled. Since the sand is interspersed with shale, it is difficult to determine the net sand thickness unless the sand is cored and analyzed.

Production History—The discovery well in the Gunsight sand in the West Burkburnett Field was the Chris Schmoker No. 1, and was drilled by the Corsicana Petroleum Company which is now known as the Magnolia Petroleum Company. The well was completed in June, 1912, for a reported initial production of 85 bbl of oil per day.

The original development of the field was from 1912 to 1926. The initial production of the wells varied from 5 bbl to 125 bbl of oil per day pumping. The daily average initial production pumping was approximately 30 bbl of oil and no water. There is approximately 2700 acres within the original productive limits of the field. The Magnolia Petroleum Company owns approximately 80 per cent of the original productive acreage, and the data presented in this paper is on Magnolia's acreage. There were 219 wells drilled on Magnolia's acreage in the West Burkburnett Field. The well status before development as a water flood project was as follows: 11 dry holes, 85 wells abandoned, 8 water input wells, 2 wells not in operation, and 113 producing wells in the Gunsight sand.

All of the wells were drilled with a rotary and casing was set from 40 to 90 ft above the top of the sand. Cable tools were used to drill a reduced hole into the sand, and a slotted or perforated liner was set through the producing sand. The casing was not cemented in the hole during the early development of the field, and this method of completion occasionally allows water from upper sands to leak around the casing shoe and into the oil producing sand. The majority of the wells were shot with 30 to 60 quarts of nitroglycerine. Some of the wells were swabbed for production on completion, but most of the wells were pumped by central powers located on the various leases.

The field had a normal decline in production until 1938. The average daily production in 1938 for Magnolia's acreage in the West Burkburnett Field was 187 bbl of oil. In July, 1936, a gas injection program was started and continued until 1942. The production increased to 258 bbl of oil per day; however, part of the increase is due to clean-out work on the various leases, and part should be credited to the gas injection program. The high cost of purchasing outside gas for injection was the main reason for discontinuing the gas injection program. A vacuum of approximately 18 in. of mercury has been pulled on the casing head of the wells since early development of the field.

During the latter part of 1943, and the first part of 1944, 8 wells were drilled on the J. G. Goins lease, 7 wells were drilled on the Chris Schmoker lease, 2 wells were drilled on the B. F. Cook lease, and one well was drilled on the L. H. Lawler lease. All of the wells drilled were cored and the samples analyzed. The wells were drilled on ten acre spacing. The wells averaged approximately 4.5 bbl of oil per day on completion tests.

Properties of the Reservoir—There is no evidence of a water table or water drive in the field, and it is believed that the small amount of water

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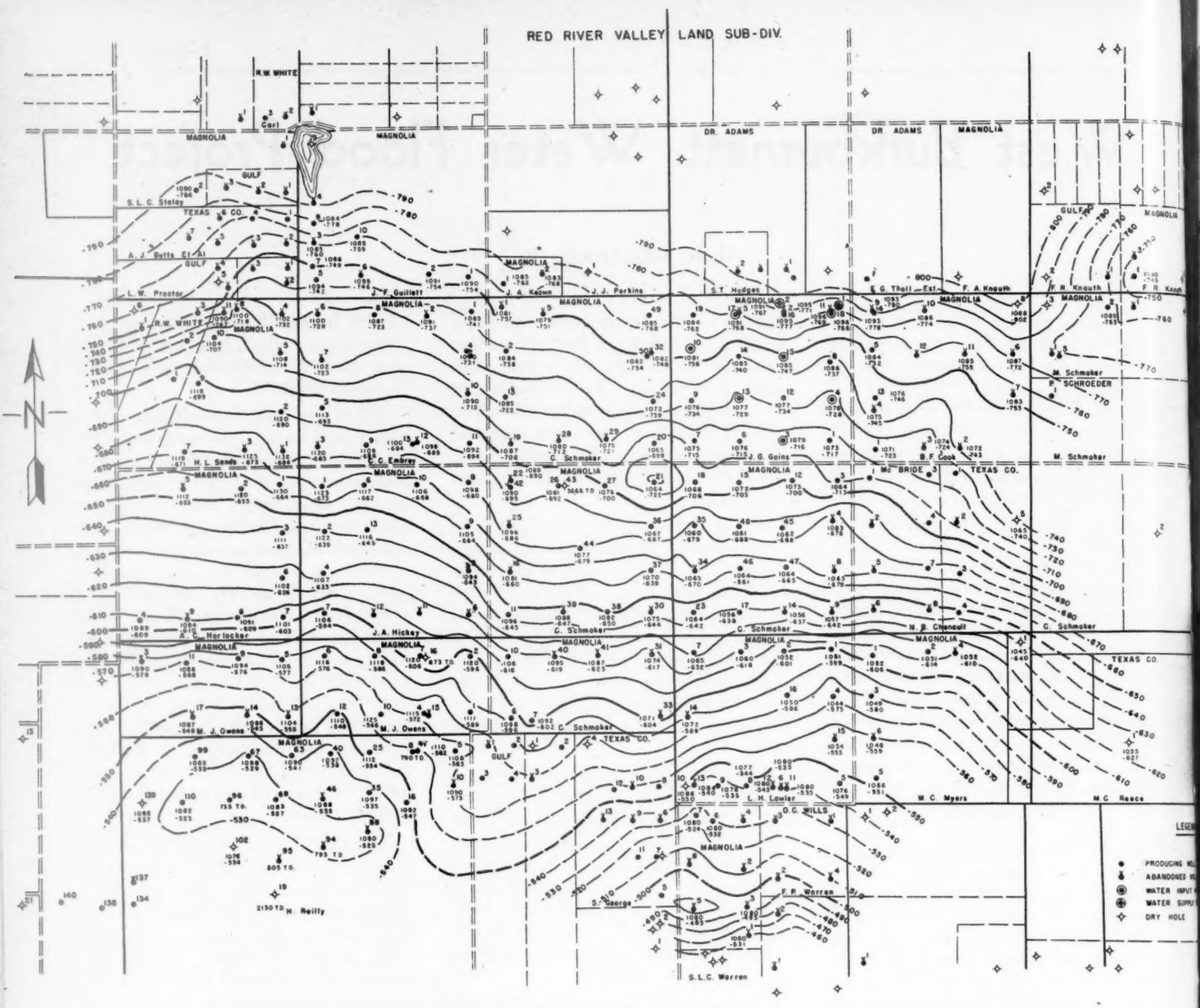
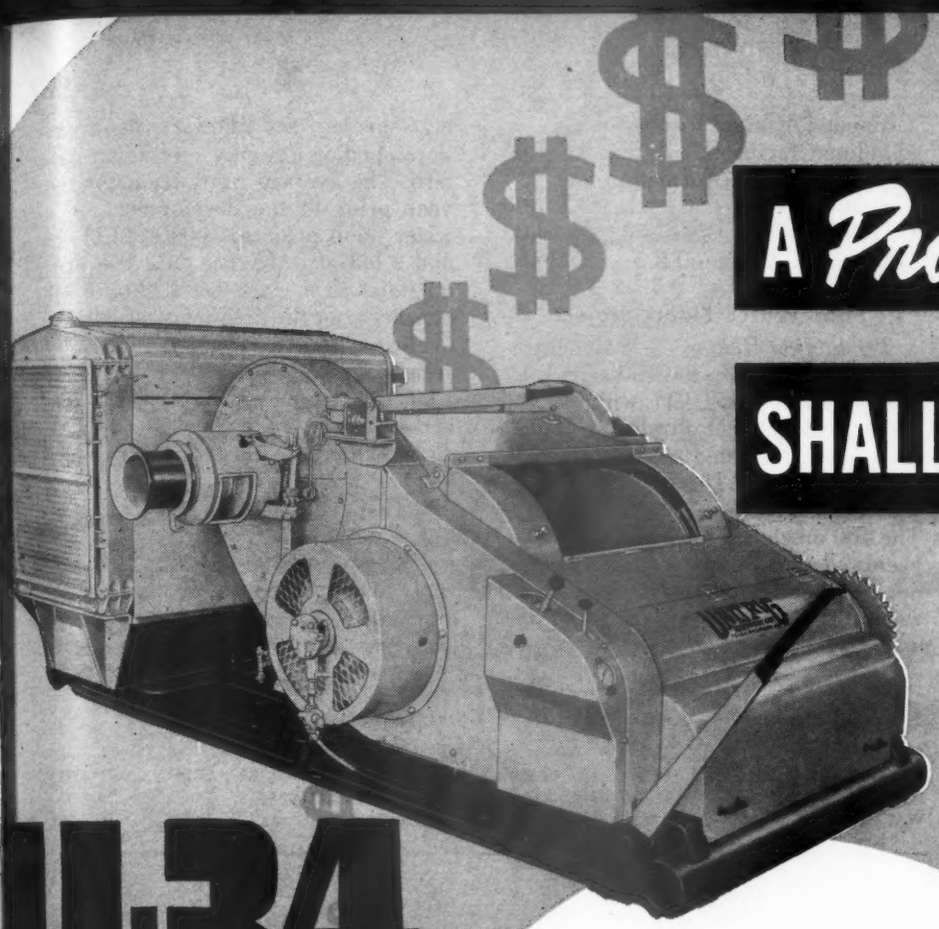


Structure map of West Burkburnett field.

produced from some of the wells is due to casing leaks or defective casing seats. It is assumed that the reservoir is of the solution gas drive type, and that the original oil in the reservoir was undersaturated. No data is available on original bottom hole pressures or gas-oil ratios; however, they were probably very low. It is the opinion of the author that the pulling of vacuum, gas injection, and gravity drainage accounts for the relatively long life of production. The shale found in the sand is interspersed and not in streaks or beds. The core analysis of samples obtained indicate that this type of shale deposit does not affect the permeability profile to the extent that excessive channeling will take place. There is a thin nonproductive lime streak approximately 1 to 3 ft in thickness in the lower part of the producing section. In some areas the lime streak is in the bottom of the section; however, in some of the wells 1 to 5 ft of oil sand is found below the lime. There is no appreciable variation in sand characteristics above or below the lime.

Permeability data was obtained on various core samples by passing air and various salinities of water through the core samples. Using the permeability to air as a 100 per cent base, the permeability to water decreased as the chloride content was reduced. The average permeability to water containing 100,000 ppm of chlorides was 73.3 per cent of the average permeability to air; whereas, the average permeability to fresh water was 30.1 per cent of the average permeability to air. After fresh water had been passed through the core samples, the average permeability to water containing 100,000 ppm of chlorides was 30.1 per cent. The results obtained from these tests indicate that a higher permeability to input water would be obtained by the use of salt water; and that once fresh water had passed through the sand, the permeability to salt water could not be restored.

Core analyses were obtained on the core samples taken from wells drilled in 1943 and 1944, and the properties of the reservoir presented in this paper is based on the data obtained. Two methods were used to obtain cores of the wells drilled. Approximately one half of the cores were taken with a rotary using a high water loss mud. The cores were flushed and the oil saturation data obtained was assumed to be indicative of the residual oil saturation after the sand has been flooded with water. One half of the cores were taken with cable tools using produced oil as the drilling fluid. The water saturation data obtained by this procedure was assumed to be the interstitial water in the sand. Cores having very



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low permeability or excessive water saturation were assumed to be non-productive.

Since the sand is interspersed with shale, the thickness as shown on the original driller's logs does not reflect the net sand thickness. The core analysis reports were used to estimate the net sand thickness. The recoveries to date on the various leases is also indicative of the net sand thickness. The reservoir properties obtained from core analysis and production data is as follows:

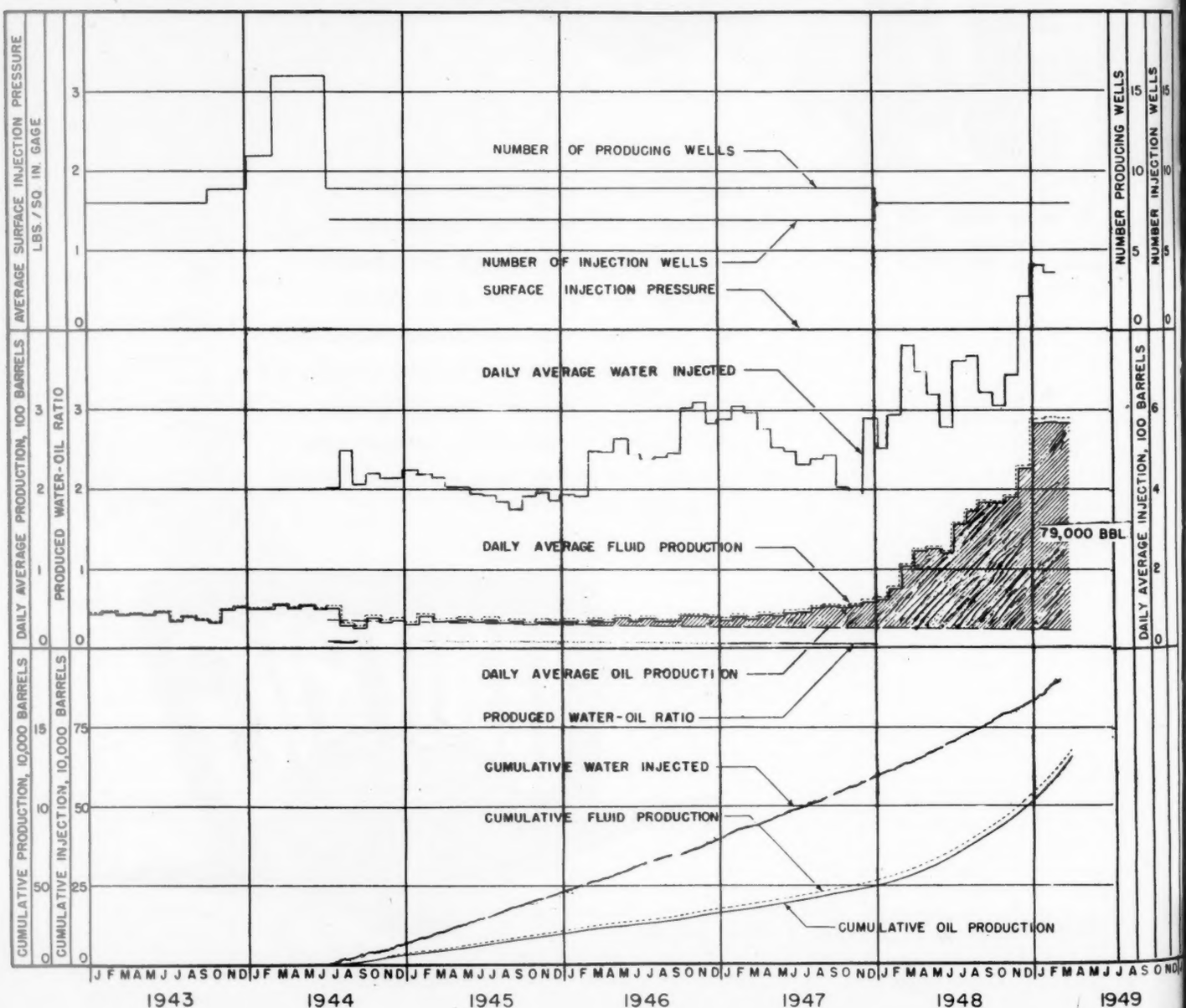
Porosity, per cent volume.....23.0
Permeability, millidarcys 72.0
Interstitial water saturation, per cent pore space.....23.0
Residual oil saturation after flood, per cent pore space.....26.0
Estimated original formation volume factor 1.06
Estimated present formation volume factor 1.00
Oil viscosity, centipoises..... 4.00
Oil gravity, API at 60 F.....39.5

Pilot Water Flood Project

Production History — Water injection was started on the 160-acre J. G. Goins lease in July, 1944, with 7 water input wells and 9 producing wells. This lease is located in the northeast part of the field. There are 138 acres within the effective water flood limits. The 160 original productive acres has been reduced to 138 effective water flood acres since no offset water input wells will be drilled to the north of the lease. The lease was drilled on ten acre spacing, and the water flood was developed on a twenty acre 5 spot pattern. The average production for the year prior to the development of a water flood project was 40 bbl of oil and 2 bbl of water per day. The production was increased to 52 bbl of oil per day after the drilling of 8 wells on the lease; however, the production decreased to 32 bbl of oil per day when 7 of the producing wells were converted for water injection. The oil production increased from 32 bbl to 59 bbl per day from July, 1944 to January, 1948. This is a net increase of 27 bbl of oil per day in 3½ years. There was no increase in water production. In January, 1948, one of the producing wells was converted for water injection. From January, 1948 to April,

Production history of Gunsight sand, J. G. Goins lease, West Burkburnett field.

POROSITY, %	23.0	OIL VISCOSITY, CP	4.00	PERMEABILITY, MD	72
INTERSTITIAL WATER SATURATION, %	23.0	OIL GRAVITY, A.P.I.	39.5	PRIMARY RECOVERY, BBL/ACRE	4,011
RESIDUAL OIL SAT. AFTER FLOOD, %	26.0	LEASE PRODUCTIVE ACRES	160	INJECTION PATTERN	5-SPOT
PRESENT FORMATION VOLUME FACTOR	1.00	WATER FLOOD ACRES	138	SPACING	10-ACRE


AVERAGE SURFACE INJECTION PRESSURE LBS./SQ. IN. GAGE
NUMBER PRODUCING WELLS
NUMBER INJECTION WELLS
NUMBER OF PRODUCING WELLS
NUMBER OF INJECTION WELLS
SURFACE INJECTION PRESSURE
DAILY AVERAGE PRODUCTION, 100 BARRELS
PRODUCED WATER-OIL RATIO
DAILY AVERAGE WATER INJECTED
DAILY AVERAGE FLUID PRODUCTION
79,000 BBL
DAILY AVERAGE INJECTION, 100 BARRELS
CUMULATIVE PRODUCTION, 10,000 BARRELS
CUMULATIVE INJECTION, 10,000 BARRELS
DAILY AVERAGE OIL PRODUCTION
PRODUCED WATER-OIL RATIO
CUMULATIVE WATER INJECTED
CUMULATIVE FLUID PRODUCTION
CUMULATIVE OIL PRODUCTION
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1943
1944
1945
1946
1947
1948
1949

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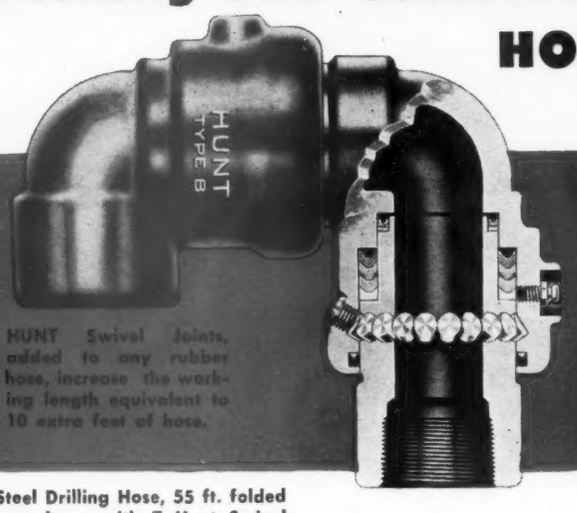

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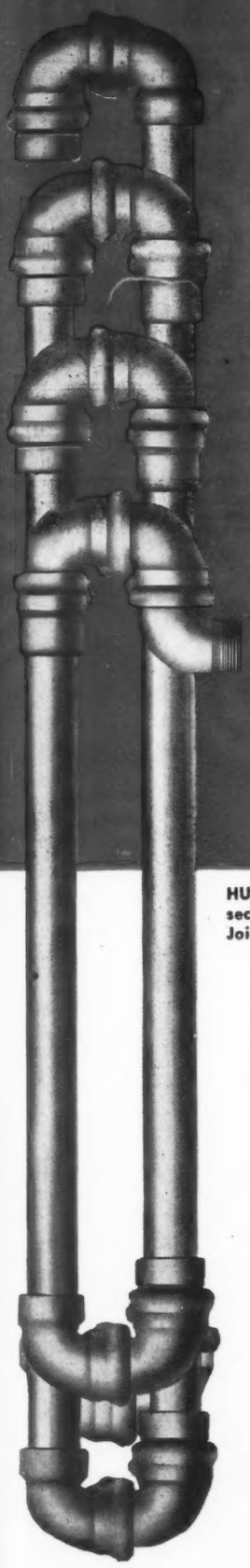

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1949, the production increased from 59 bbl to 283 bbl of oil per day. This is a net increase of 224 bbl of oil per day in 15 months. Daily peaks of production have been as high as 320 bbl of oil per day, and production rates from 400 bbl to 450 bbl of oil per day are expected before the end of 1949. It should be noticed that there has been no appreciable increase in water production to date.

The cumulative recovery prior to water flooding the J. G. Goins lease was 629,673 bbl for the 157 original productive acres. This is a recovery of 4,011 bbl per acre. The cumulative recovery since water flooding has been 129,000 bbl of oil. It is estimated that 50,000 bbl of the oil recovered, since the start of water flood operations, would have been recovered by primary methods; and 79,000 bbl of the oil is credited to water flooding. Based on the 138 effective water flood acres, there has been a recovery of 934 bbl per acre since water injection was started. Based on the per acre recovery, this is approximately 23 per cent as much oil as had been recovered prior to water flooding.

Water Injection—The water injection rates are based on the net sand thickness present in the water input well. The average initial rates of injection were approximately 4 to 5 bbl per day per foot of sand; however, as the project continued, average injection rates were increased to approximately 8 bbl per day per foot of sand. Since additional input water is not available at the present time, increased rates have not been possible.

The cumulative water injected to April 1, 1949, is 909,000 bbl. Approximately 7 bbl of water has been injected for every barrel of oil produced since the water flood was started. The first major increase in oil production occurred approximately 3½ years after water injection was started. At this time, it was estimated that approximately 71 per cent of the void space in the reservoir had been filled with input water. The estimated void space in the reservoir is the sum of the cumulative oil production, cumulative water production, and the shrinkage of the oil in place. As of April, 1949, the estimated void space filled by input water is 96 per cent. Since the void space was 71 per cent filled with input water, any major change in the daily water injected resulted in a change in the daily oil production.

In the near future, bottom hole pressures are to be obtained at regular intervals on all producing wells to study and regulate reservoir performance.

Magnolia Petroleum Company's C. Schmoker lease, West Burkburnett field, Wichita County, Texas.

Sample Number	Well Number	Permeability To air	Depth	Permeability to water: 100,000 ppm	25,000 ppm	2,000 ppm	Fresh water	100,000 ppm*
1	57	0.4	1846.5	0.2	0.08	0.1	0.1	0.1
2	56	2.5	1728.5	1.8	2.3	0.6	1.4	1.4
3	61	2.0	1774.5	2.5	1.3	1.3	1.1	1.3
4	58	3.6	1834.5	1.8	1.5	1.2	1.2	1.6
5	57	8.5	1855.5	4.1	3.5	3.4	2.7	2.7
6	54	15.	1701.5	8.0	6.3	5.1	2.9	3.0
7	61	21.	1773.5	11.	9.3	13.	9.4	11.
8	60	32.	1809.5	23.	16.	15.	6.7	9.3
9	61	51.	1758.5	28.	17.	17.	6.5	15.
10	60	59.	1801.5	58.	47.	4.0	2.1	3.7
11	55	62.	1742.5	48.	40.	31.	21.	37.
12	60	64.	1807.5	56.	74.	60.	43.	32.
13	61	83.	1760.5	43.	58.	52.	41.	17.
14	61	79.	1766.5	69.	40.	22.	7.2	10.
Averages		34.5 (100%)		25.3 (73.3%)	22.6 (65.5%)	16.1 (46.7%)	10.4 (30.1%)	10.4 (30.1%)

*This is the permeability at 100,000 ppm after fresh water has been passed through the samples.

J. G. Goin's No. 12, West Burkburnett field, Wichita County, Texas.

Core analysis.*

Sample number	Depth feet	Permeability Millidarcys	Porosity per cent	Residual Liquid saturation % pore space: Oil	Water	Chloride, PPM in pore water
1	1812.0	14	19.9	29.1	28.1	94,000
2	12.5	48				
3	18.0	204	25.3	69.2	12.6	122,000
4	18.5	125				
5	19.0	125	20.9	69.8	13.9	124,000
6	19.5	124				
7	21.0	107	20.6	71.9	19.4	124,000
8	21.5	50				
9	22.0	110	21.1	76.3	17.0	120,000
10	22.5	70				
11	23.0	40	20.2	72.8	18.3	143,000
12	23.5	90				
13	24.0	75	21.2	64.6	20.7	112,000
14	24.5	77				
15	25.0	147	20.2	70.7	17.8	147,000
16	25.5	78				
17	26.0	107	19.4	70.7	23.2	121,000
18	26.5	88				
19	27.0	82	22.1	68.0	19.5	108,000
20	27.5	77				
21	28.0	105	20.8	66.9	21.6	103,000
22	28.5	31				
23	29.0	52	23.0	71.7	17.4	140,500
24	29.5	123				
25	31.5	112	22.1	70.2	14.9	175,000
26	31.7	38				
27	32.0	45	18.7	68.0	16.0	173,000
28	32.5	33				
29	33.0	18	17.6	45.4	22.7	169,000
30	33.2	6				

*Cored with cable tools in produced oil.

Development Program

Drilling — The West Burkburnett Field water flood project is to be developed during a three-year period. Eighty-five wells will be drilled to develop the project. At the present time, the second year's drilling program is in progress. The producing and water input wells are being drilled on 10-acre spacing, and several of the abandoned well locations are being redrilled in order to develop the water flood pattern. The water supply wells are to be drilled on 160-acre spacing.

There is an 800-ft producing sand in the southwest part of the pool, and core data is to be obtained on the sand as the deeper wells are drilled. If the 800-ft sand proves to be favorable for water flooding, it is possible that the same wells may be utilized at a later date to water flood this sand.

The wells are being drilled with a rotary and core data is being obtained on all wells. All water input wells are to be cored with a rotary using a high water loss mud. All producing wells are to be cored with cable tools in produced oil. It is the opinion of the author that the core data is necessary in order to study and regulate an efficient water flood project.

When the project is completely developed, there will be 102 producing wells and 97 water input wells on a 5-spot pattern. There will be approximately 1680 acres within the effective water flood limits. The estimated effective water flood limits is a line connecting all operating wells on the edge of the field.

Completion Practice—All wells are to be completed with the casing set on top of the Gunsight sand. Four-inch

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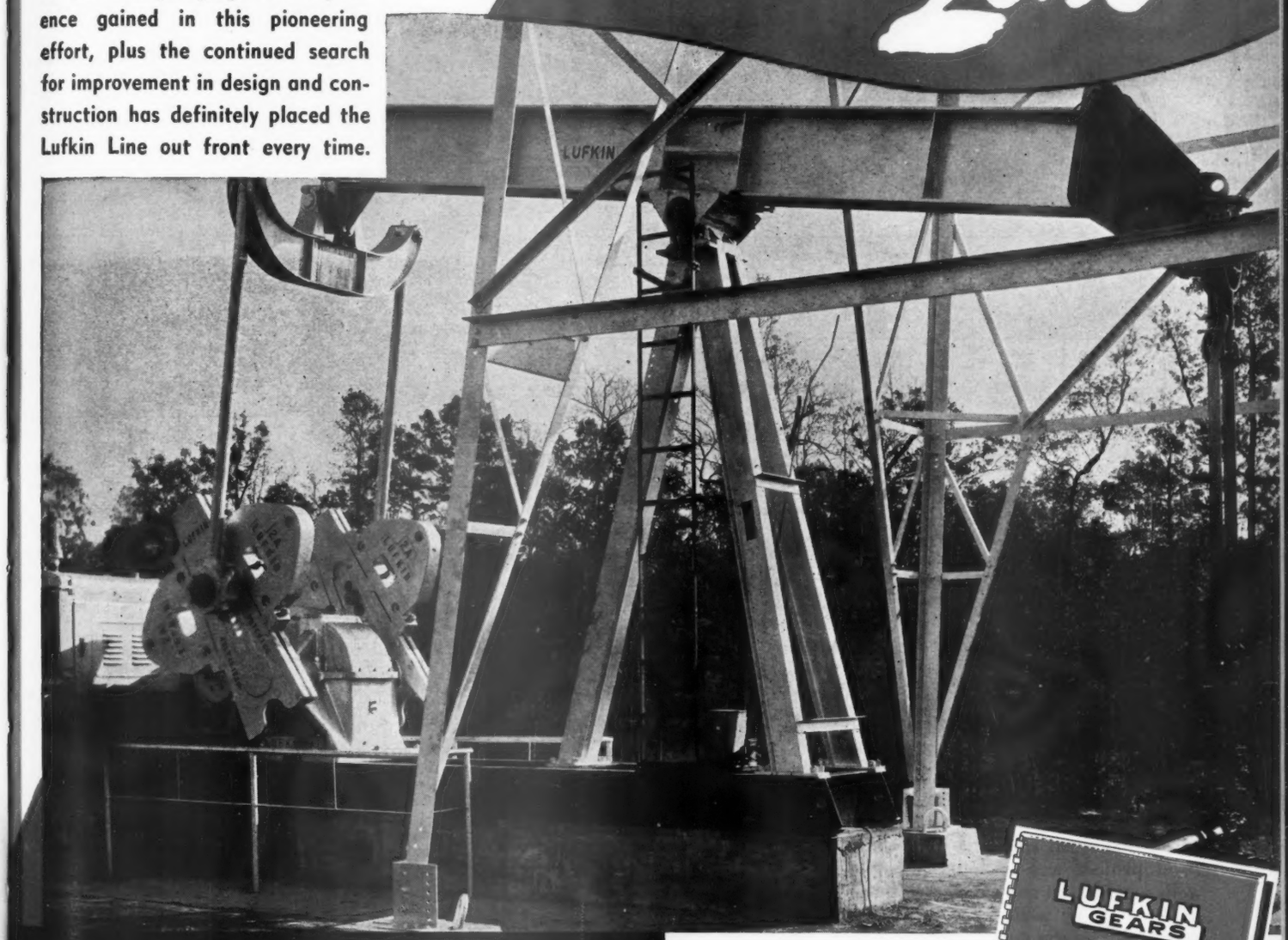

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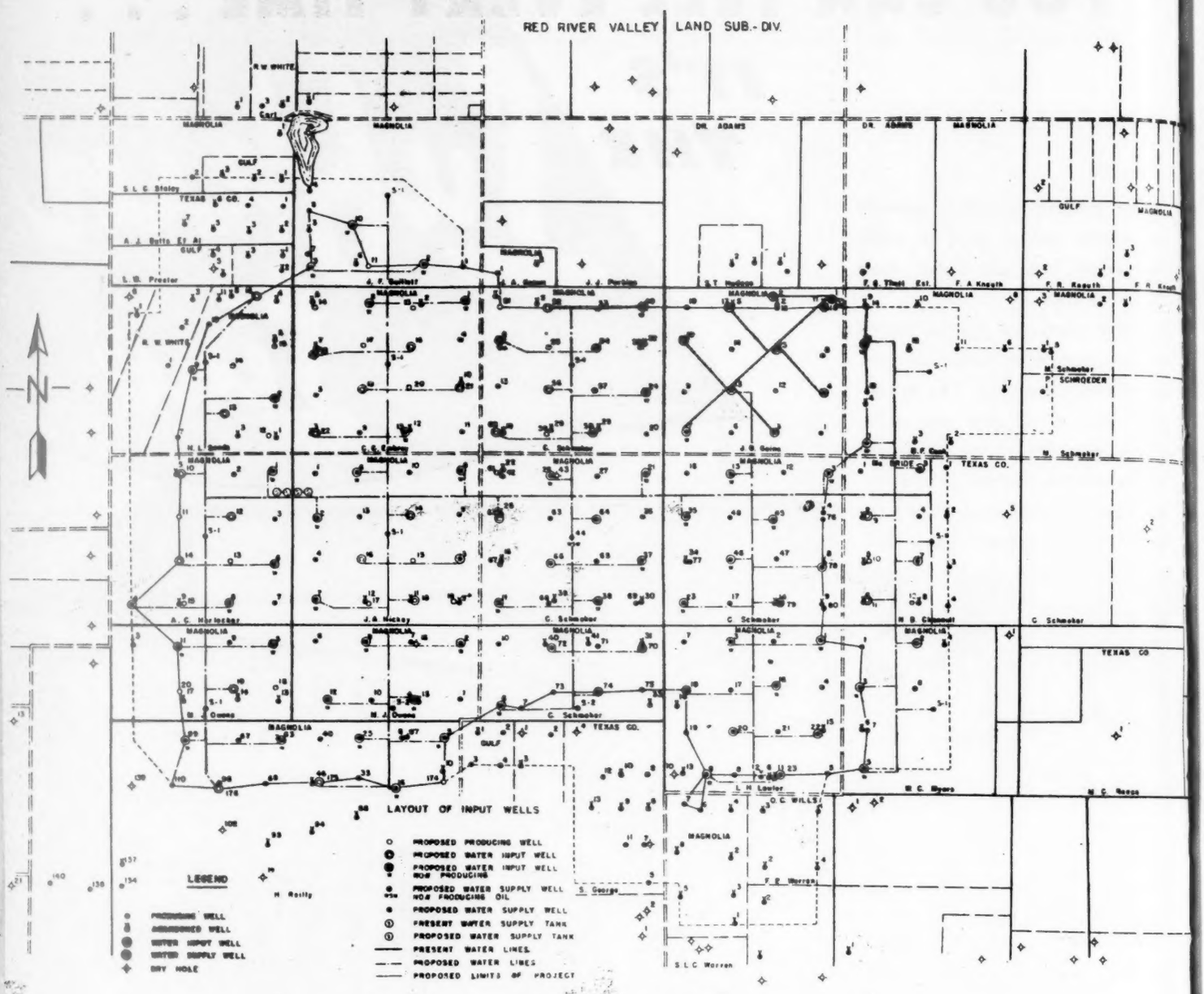

Water flood development map of West Burkburnett field.

line pipe is to be used for casing in the water input wells. The producing formation in all injection wells is to be shot with one to two quarts of nitroglycerine per foot of sand. The information obtained from the pilot water flood project was that the injection wells would take more water with less pressure if the wells were shot. It is the opinion of the author that on a 10-acre spacing pattern that shooting of the input wells will not be conducive to channeling of input water; however, it is possible that on a closer spacing pattern, shooting of the input wells may channel injected water to producing wells. The producing wells are not shot on completion.

Since the casing was not cemented in the wells drilled during the original development of the field, a liner is to be cemented on top of the sand in all wells to be converted from producing wells to water input wells.

The producing wells are completed using 7-in. casing. Two-inch line pipe is used for tubing, and most of the wells are equipped with pumping jacks connected to the central powers located in the field. No tubing or packers are used in the injection wells, and the water is injected directly into the casing. Very simple surface connections are used on the water input wells. All water input wells are equipped with a water meter and a regulating valve.

The water supply wells are completed by cementing 7-in. casing through all formations showing water, and gun perforating the water bearing sands as indicated on the electric log. Two and one half and three inch tubing has been used in the water supply wells. At the present time, individual pumping units are being used to produce the water. In the near future, an electric centrifugal pump is to be used on one of the water supply wells.

Water Input System

Water Source and Distribution — There are approximately 150 feet of water sands between 0 and 1700 ft in the water flood area. The water analysis indicated 99,600 ppm of chlorides. It should be noticed that the permeability of the sand to water with this chloride content is approximately 73 per cent of the permeability of the sand to air. The water has been satisfactory and requires no treatment before injection; however, iron oxide does precipitate out in the distribution lines. The water distribution lines

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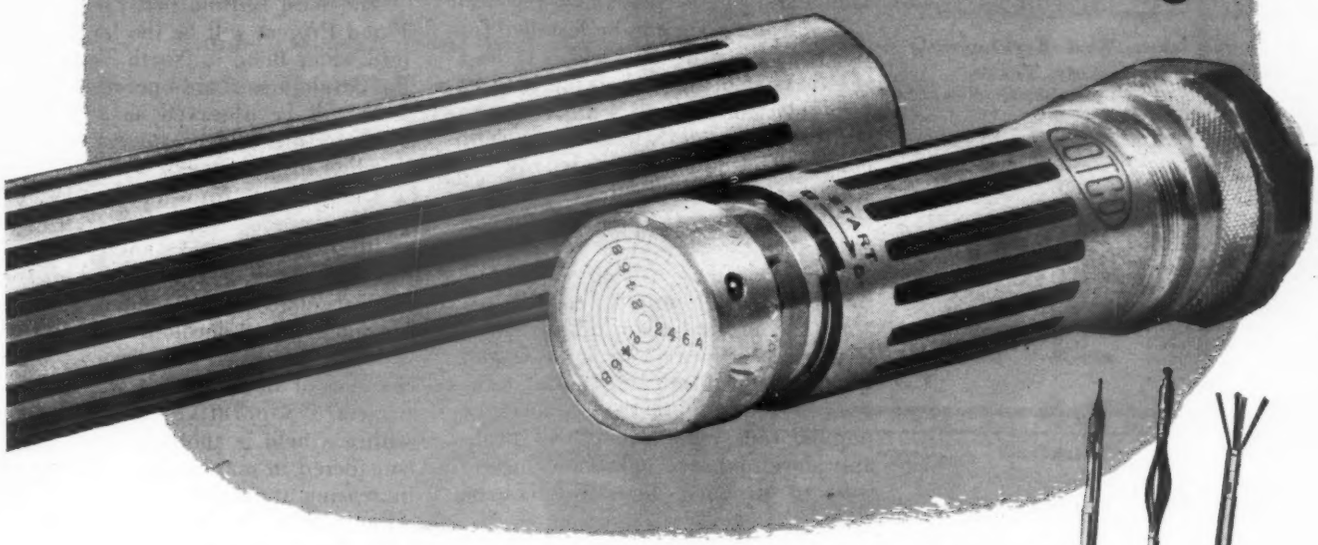

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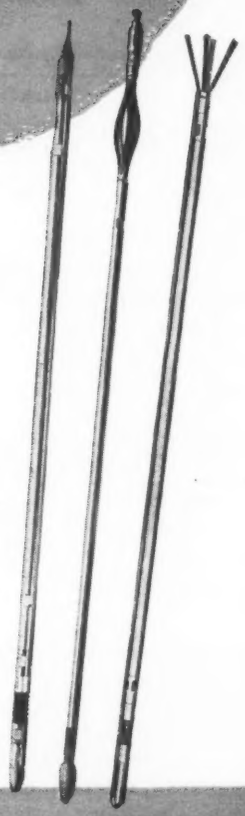

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J. G. Goin's No. 13, West Burkburnett field, Wichita County, Texas.

Core analysis.*

Sample Number	Depth Ft	Permeability Millidarcys	Porosity %	Residual Liquid Saturation % Pore Space Oil	Water
1	1809.5	170	25.7	20.2	61.7
2	10.5	112	26.1	29.9	52.7
3	11.5	111	27.3	26.3	53.2
4	12.5	151	24.5	28.1	51.3
5	13.5	64	23.1	32.9	51.2
6	14.5	53	20.5	27.3	50.7
7	15.5	44	23.2	31.4	54.8
8	16.5	43	22.0	34.5	55.1
9	17.5	88	25.2	30.5	51.7
10	18.5	94	24.2	26.0	57.5
11	19.5	156	27.3	29.2	49.0
12	20.5	57	23.4	29.1	44.0
13	21.5	52	24.2	24.4	59.9
14	22.5	89	21.5	27.9	54.3
15	23.5	0	4.8	0.0	12.5
16	24.5	129	26.2	26.7	52.0
17	25.5	28	23.8	29.4	49.6
18	26.5	7	19.5	29.3	43.5

*Cored with rotary in high water loss mud.

J. G. Goin's lease, West Burkburnett field, Wichita County, Texas.

Water analysis.

	Parts per million	Equivalent parts per million
Silica	420.00	
Fe and Al Oxide	368.00	
Magnesium	2234.67	183.69
Calcium	10943.26	546.07
Sodium		2080.57
Carbonates	0.00	0.00
Bicaronates	24.84	0.41
Sulphates	57.61	1.20
Chlorides	99600.00	2808.72
Hydroxides		
Total solids weighed	152480.00	
Co_3 and HCO_3 Burned	24.84	
Suspended Solids		
Total	152504.84	

Free CO_2 ..... 89.81 ppm
Non incrusting solids .... 1014.39 lbs/1000 gallons
Incrusting solids ..... 332.24 lbs/1000 gallons
S. G. ..... 1.116 pH 5.6

and injection wells are acidized with a 15 per cent solution of HCl acid to dissolve the precipitate when intake capacity decreases below desired rates of injection.

At the present time, some fresh water is used for injection; however, as additional salt water supply wells are drilled, the use of fresh water will be discontinued. The estimated total water to be injected, after complete development of the field, is 6000 to 10,000 bbl per day.

The water system on the pilot water flood project is a closed system with gravity distribution lines. The water is pumped from the wells to a storage tank with an oil seal on top of the water. Gravity distribution lines are connected from the tank to the injection wells. The water system for the field is to be a closed system with gravity distribution; however, the water supply wells are to pump directly into the water system at a point nearest the water supply well. The main line through the field will be 6-in. pipe, and the main laterals will be 3-in. pipe. Laterals 1½ in. will be connected to the injection wells. The storage tanks for the system will be surge tanks for any excess water that is produced and not used for injection. Automatic liquid level controls will be installed on the storage tanks to regulate the amount of water required from the supply wells.

Protective Coatings — Three-inch transite pipe was used for the main water distribution line on the pilot water flood project to prevent corrosion. The main disadvantage to this type is that it cannot be used in a pressure system. At the present time, the pilot water flood project is not under pressure; however, it is possible that pressure will be required at a later date.

The water system to be installed for the West Burkburnett Field is to be a plastic coated pipe. The pipe is to be sand blasted, cleaned with a carbon tetrachloride solution, and plastic coated. The outside is to be covered with a bitumastic coating to protect against soil corrosion. All electric centrifugal pumps are to be coated with plastic since they will be submerged in the salt water supply wells.

At the present time, no corrosion has been observed on sucker rods and tubing in the producing wells; however, corrosion of the subsurface pumps, rods, and tubing will probably develop when it becomes necessary to produce large volumes of water.

Operating Practice

It is the opinion of the author that the personnel caring for a water flood project is a very important factor in operating and regulating an efficient water injection program. Accurate data on operations is a necessity for evaluating the results obtained.

Portable testing units are used in the West Burkburnett Field to obtain periodical tests on producing wells. The testing of the wells often indicates that a pump should be pulled, that excessive paraffin may be present in the lines or tubing, or that the well needs cleaning out. The water injection wells are checked daily to record water meter readings and report possible leaks in the water system. Accurate data on oil production, water injection, and work performed on the lease is recorded daily and submitted to the engineering department. If it is necessary, the sand in the injection wells is back washed by lowering the static fluid well in the well and allowing the water to move from the formation into the well bore.

Some of the producing wells are to be placed on individual pumping units if the central powers are overloaded as a result of the expected increase in fluid production. A gathering system is to be installed to return all produced water to the water input system.

Cooperative Water Flood Agreement

A cooperative water flood agreement has been submitted to the offset operator to water flood equitably across lease lines. The agreement stipulates that each operator is to have an equal number of water input wells along the property line and that agreement is to be reached by an engineering committee on injection rates for offset wells.

Conclusions

The West Burkburnett Field Water Flood Project will be the largest pattern water flood in North Texas, and the development and operation of the field will be observed as a possible guide to further development of water flooding in this area.

The necessity for obtaining data on geology, production history, reservoir properties, and sources and characteristics of water is emphasized in the evaluating of a water flood project. Completion and development practice should be outlined in order to reduce the cost of developing a water flood project. Cooperative water flooding within a field is another factor to be considered in maintaining equity and increasing the total recovery of oil. After a field has been developed for water flooding, one of the most important factors in the results to be obtained is good operating practice.

Acknowledgment

The author sincerely appreciates the assistance given by Verdun M. Leonard, petroleum engineer, W. L. Haseltine, district geologist, and Miss Rita Chaffee, secretary. Appreciation is also extended to the management of the Magnolia Petroleum Company for permission to publish this paper.

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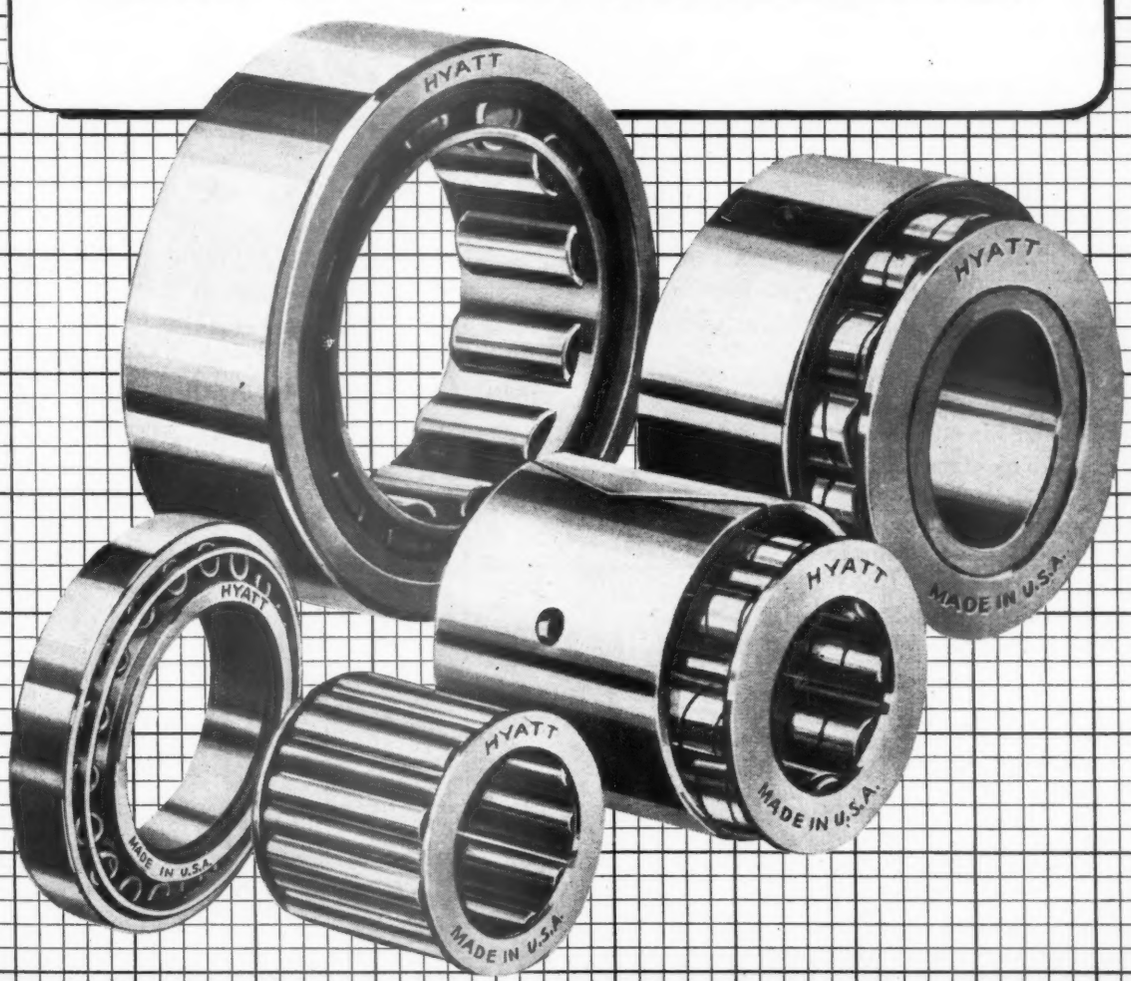


HYATT ROLLER BEARINGS

Electric Log Analysis In the Rocky Mountains*

M. P. TIXIER†

Abstract

A method of obtaining a good approximation of the water-saturation and porosity of the reservoir rocks encountered in the Rocky Mountains is discussed.

The method makes use exclusively of data derived from the resistivity and S. P. logs. It is based first, on the determination of an empirical relationship between water saturations in the uncontaminated formation and in the invaded zone, and, second, on results from field experiments regarding the relationship between S. P. deflections and the resistivities of mud and formation water.

Several actual examples of the application of the method are described.

Introduction

THE fundamental relation for the quantitative study of electrical logs, as given by Archie, is:

$$R_t = \frac{F \times R_w}{S^2} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Where:

R_t is the true resistivity of the formation under investigation.

R_w is the resistivity of the formation water.

S is the water saturation in the pore spaces of the formation (fraction of voids filled).

F is the formation factor.

Archie reports that approximately:

$$F = 1/p^m \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Where:

p is the porosity.

m is a cementation factor.

A great amount of work has been done which shows that this relation is usually correct when all of the porosity is effective. A correction is necessary at low water saturations, when the formation has a large amount of non-effective porosity. However, to use these relations, it is usually necessary to determine R_w from a sample of the formation water and F by an analysis of some cores from the formation. On the other hand, if the lithology and the water salinity are supposed to be approximately constant throughout the formation under study, and, if a section of the same formation completely saturated with formation water is available, the following relation may be used:

$$S = \left(\frac{R_o}{R_t}\right)^{1/2} \quad . \quad . \quad . \quad . \quad (1\text{-A})$$

Where:

R_o is the resistivity of the formation when the pore spaces are filled 100 per cent with the formation water.

The purpose of the present paper is to discuss how the water saturation may be deduced from the analysis of electrical logs alone, when the values of R_o, R_w and F are not available, which is a frequent case.

Analysis of Resistivity Curves

1. In holes drilled by the rotary method, when a permeable formation is traversed by the bit, part of the oil or water present in the formation surrounding the hole is flushed out by the mud and replaced by mud filtrate. This portion of the formation is known as the invaded zone.

Considering only the invaded zone, we can write from equation (1):

$$R_i = \frac{F \times R_z}{S_i^2} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

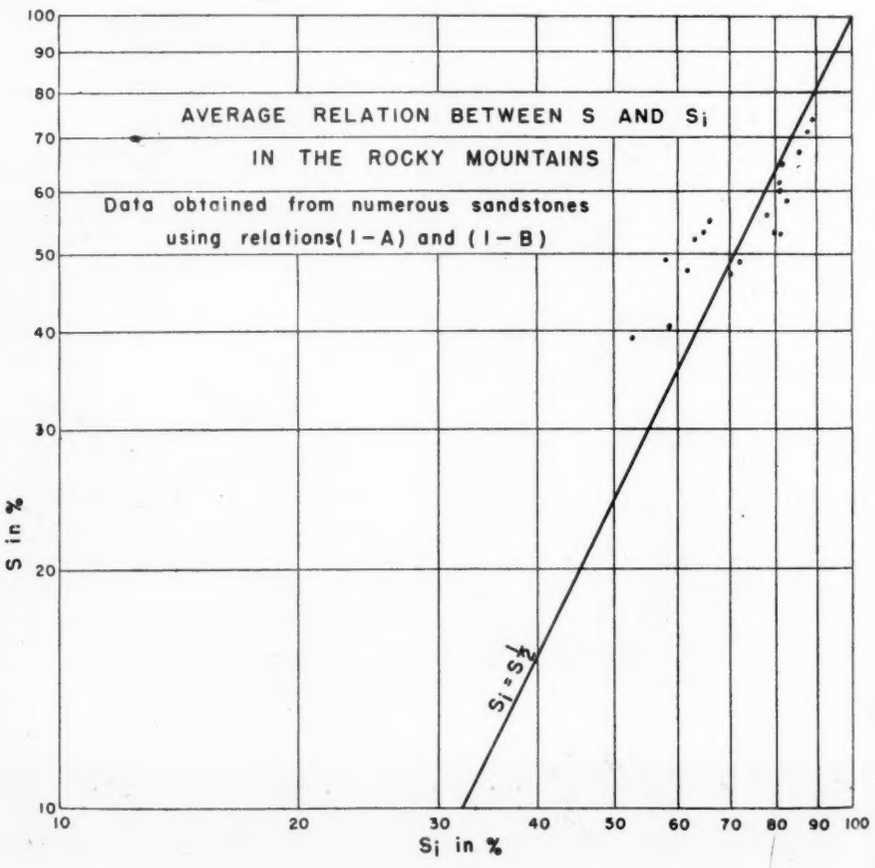
Where:

R_i is the resistivity of the invaded zone at the level under investigation.

R_z is the resistivity of the water in the invaded zone.

S_i is the water saturation in the invaded zone (fraction of voids filled) at the level under investigation.

FIG. 1.



*Paper presented before the Spring Meeting of the Pacific Coast District, Division of Production, American Petroleum Institute, Biltmore Hotel, Los Angeles, California, May 12 and 13, 1949.

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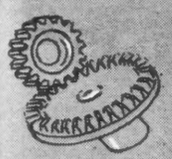

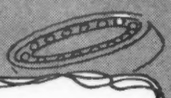

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Then, dividing relation (3) by relation (1), we obtain:

$$\frac{R_i}{R_t} = \frac{R_z}{R_w} \frac{S^2}{S_i^2} \text{ or}$$

$$\frac{S^2}{S_i^2} = \frac{R_i/R_t}{R_z/R_w} \quad . \quad . \quad . \quad . \quad (4)$$

from which the formation factor has been eliminated.

2. If the lithology of the formations and the resistivity of the water in the invaded zone are supposed to be approximately the same throughout the formation, then:

$$S_i = \left(\frac{R_{io}}{R_i}\right)^{1/2} \quad . \quad . \quad . \quad . \quad (1\text{-B})$$

R_{io} being the resistivity of the invaded zone at the water level.

Several horizons were selected in the Rocky Mountains where the ratios $\frac{R_o}{R_t}$ and $\frac{R_{io}}{R_i}$ could be determined from the electrical logs. The corresponding values of S and S_i, deduced from equations 1-A and 1-B, when graphically plotted against each other, as in Fig. 1, appear to be related by the equation:

$$S_i = S^{1/2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

It is noted that the oil displacement expressed by the above relation may not hold true everywhere. It seems that the oil displacement in the invaded zone increases with the permeability, and S_i more nearly approaches $S^{1/5}$ for highly permeable formations.* In limestones and in depleted sands the oil displacement may also be greater than expressed by relation (5). For the above reasons relation (5) is primarily applicable to the Rocky Mountains where permeabilities in sandstones are usually small.

3. Once preliminary observations have proved that S and S_i can be related by equation (5), equation (4) can be simplified, and the value of water saturation in the oil bearing zone can be given by:

$$S = \frac{R_i/R_t}{R_z/R_w} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

4. By definition, R_z was called the resistivity of the water in the invaded zone. It will now be shown how this value of R_z can be approached.

The mud filtrate is not the only water existing in the invaded zone, since the formation water cannot be entirely displaced by the mud, furthermore, there is not complete diffusion between the mud filtrate and the formation water.

In all sands some pore space exists into which oil migration cannot take place. Such volume represents the non-effective porosity. This space is filled with the original formation water, and it is likely that the mud filtrate cannot displace such water. On the contrary, in the volume represented by the effective porosity, the mud filtrate can displace some of the hydrocarbons which may be present and can displace, or diffuse with, the formation water.

As long as the mud filtrate and formation water have resistivities of the same order, only a small error will be made in assuming that all the water in the invaded zone is equivalent in resistivity to the resistivity of the mud filtrate. This is no longer true when the mud filtrate has a resistivity much larger than that of the formation water. It may be assumed in this case that the conductivity of the invaded zone at the water level is the total of the conductivity corresponding to the water which has filtered into the pore spaces plus the conductivity of the original formation water remaining in the pores. Then, if z is the ratio of the volume of formation water to the total volume of all the water in the pores, we obtain:

$$\frac{R_z}{R_w} = \frac{R_m/R_w}{(1-z) + z\,R_m/R_w} \quad . \quad (7)$$

Where:

R_m = resistivity of the mud filtrate.

R_w = resistivity of the formation water.

In the Rocky Mountains z appears to average between 5 per cent and 10 per cent (0.05 to 0.1) in most formations; the data from core analysis show that the proportion of non-effective porosity has a value of the same order. When a large amount of colloids are found in the formation, a larger value for z should be taken since the non-effective porosity increases with the amount of colloidal material.

Fig. 2 shows several curves which give the value of $\frac{R_z}{R_w}$ in terms of $\frac{R_m}{R_w}$ according to equation (7) for different values of z ranging from .025 to 0.1.

According to equation (6), the determination of water saturation requires the determination of R_i/R_t and R_z/R_w. The former ratio is given by the resistivity logs, and the latter is deduced from R_m/R_w, this last ratio being given by the S. P. curves as explained below.

6. Determination of R_i/R_t.

It should be remarked that the values of R_i and R_t are not always given directly by the electrical log.

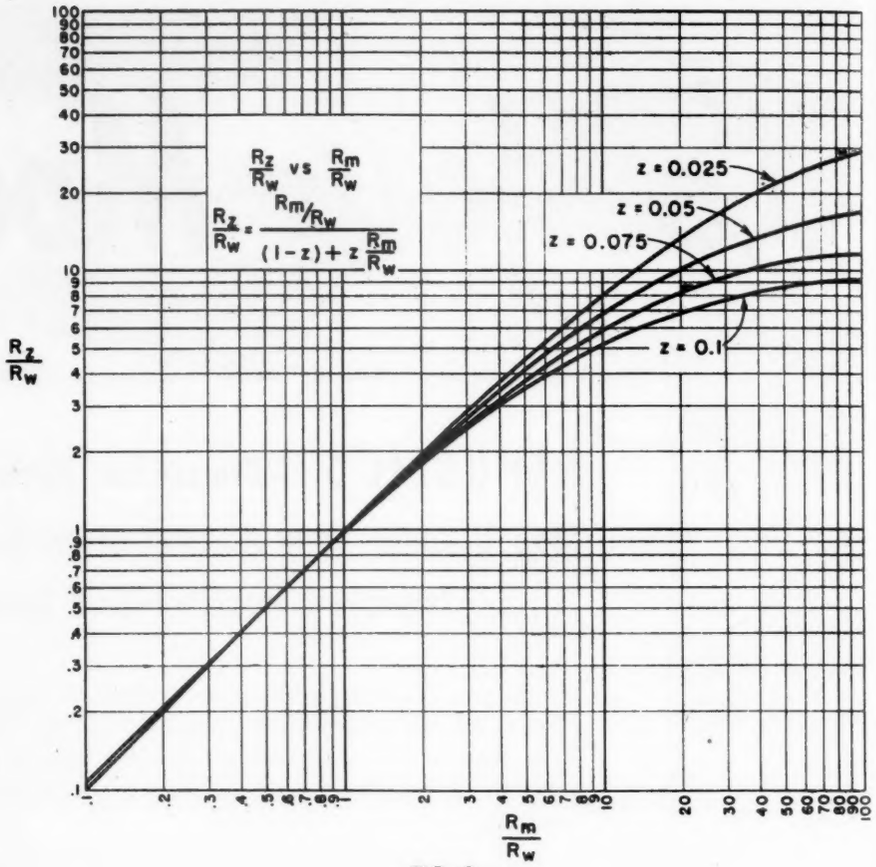

FIG. 2.

*G. E. Archie, "Electrical Resistivity an Aid in Core Analysis Interpretation," AAPG Bulletin, Vol. 31, No. 2, February, 1947.

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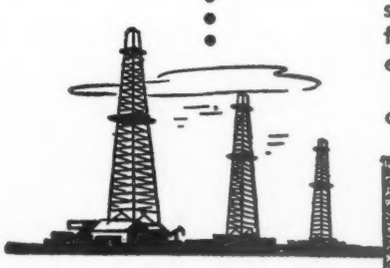

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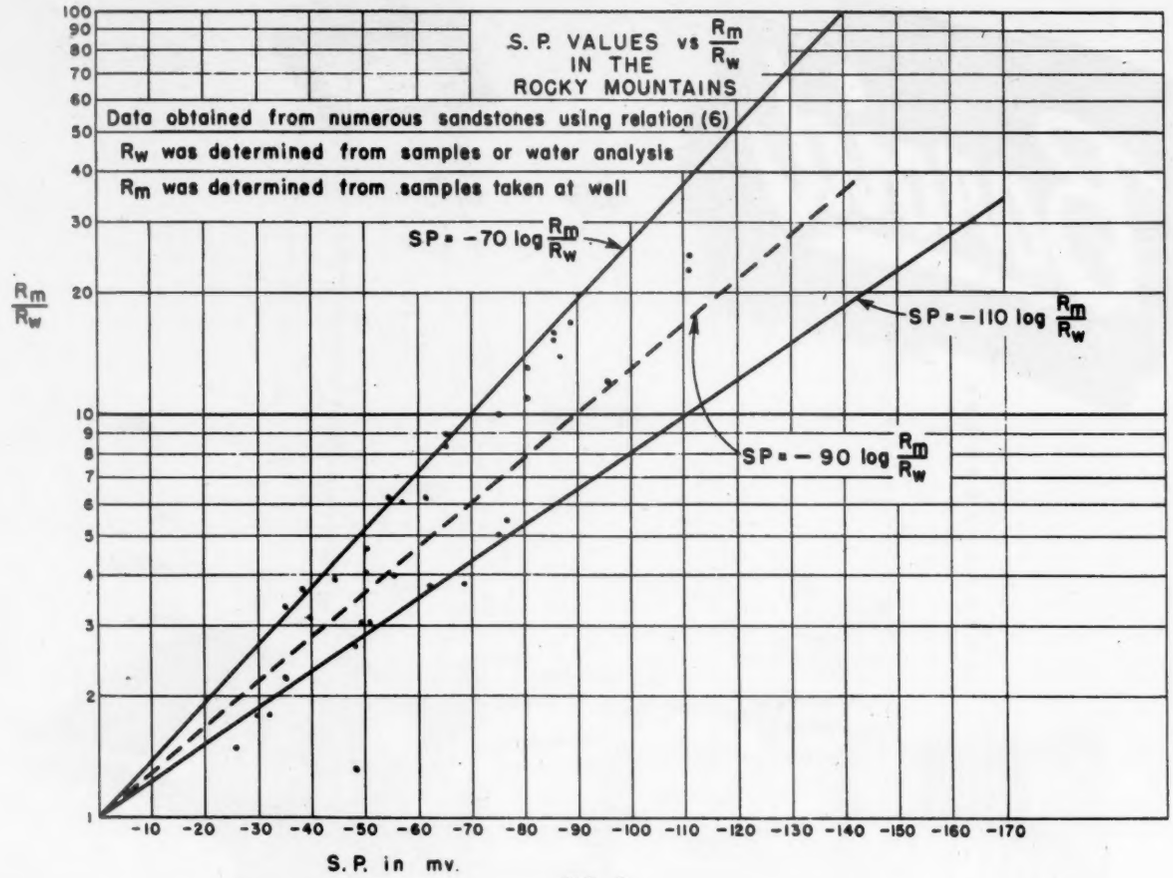

FIG. 3.

but corrections can be made by means of the resistivity departure curves.

(a) The order of magnitude of R_i, the resistivity of the invaded zone, is usually obtained from a resistivity curve with a short radius of investigation. Generally, the short normal curve is the curve to be used for this purpose. Since the values of R_i are generally high, the apparent values may be too low because of hole influence, but this can be taken care of by means of the departure curves.

(b) Similarly, approximate values of R_t, the true resistivity of the formation, are usually determined from a curve with a long radius of investigation. The lateral is the curve used in practice for this purpose. The electrode spacing is usually long enough so that in front of formations of comparatively low resistivity, the apparent value given by the lateral curve is close to the true value, and R_t/R_m can be taken equal to R_{I_L}/R_m. For high resistivities, a correction is necessary which can be obtained from the departure curves. The resistivity of the mud used to make the corrections must be taken at the formation temperature.

It must be recalled here that the resistivity of thin beds is not correctly measured with a large spacing. When the bed thickness is too small for the lateral device to be safely used, the value of R_t may be obtained from the readings of the long normal by a careful application of the departure curves.

Note: Relation (1) applies most accurately for large water saturations. In highly permeable formations, the water saturation may be relatively low and relation (1) may be better expressed, for example, by:

$$R_t = \frac{F \times R_w}{S^{1.5}}$$

However, in this case the relation between S and S_i is also different. In the preceding discussion, $S_i = S^{1/5}$ which, as already explained, represents a small displacement of oil. In the case of high permeability, the oil displacement is greater, and as found in few cases, S_i approaches $S^{1/5}$ in value. Referring to equation (4), it can be seen, even then, that equation (6), $S = \frac{R_i/R_t}{R_z/R_w}$, is still approximately correct.

For this reason, the method should permit a good approximation of the water saturation in most cases. Exceptions will be found in some very permeable limestones, or in depleted sands where most of the oil may be displaced in the invaded zone.

Analysis of the S. P. Curve

The relationship between S. P. deflection and the resistivity of mud and formation waters has already been extensively studied, and the most valuable contribution to this matter, both from the theoretical and experimental standpoints, is the work of M. R. J. Wyllie.*

The relationship between these variables can be expressed in the equation:

$$SP = K \log \frac{R_m}{R_w} \quad . \quad . \quad . \quad . \quad (8)$$

where SP is the amplitude of the S. P. deflection measured from the shale line.

An empirical comparison of the values of SP read on the SP logs and the corresponding values of $\frac{R_m}{R_w}$ has been carried out in the Rocky Mountains. This study has been difficult for the following reasons:

(1) The mud resistivity is obtained from a sample of the mud at the well. It is likely that many samples were only a poor representation of the mud in the hole at a given level.

(2) Many water analyses are not reliable because of contamination and poor sampling.

(3) It is usually assumed that the

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same water exists in a given formation at all points in the same field. This is not true in every case, and some variation may be found even within a particular formation. The resistivity of the formation water can be calculated from the water analysis. The amount of each constituent being converted into an equivalent amount to NaCl.

It has been found that most S. P. values recorded in the Rocky Mountains could be plotted in the area enclosed between the curves representing the following two equations (Fig. 3):

$$SP = -70 \log_{10} \frac{R_m}{R_w}$$

$$SP = -110 \log_{10} \frac{R_m}{R_w}$$

The average line would have the equation:

$$SP = -90 \log_{10} \frac{R_m}{R_w} \quad . \quad . \quad . \quad (9)$$

It must be pointed out that the relative error on the determination of $\frac{R_m}{R_w}$ from equation (8) due to an inaccurate value of coefficient K increases with SP. Since in the Rocky Mountains the SP values are generally small, the error on $\frac{R_m}{R_w}$ is on the average smaller than it might be in other areas where S. P. deflections are greater.

Calculation of the Saturation

It can be seen from equations (6), (7), and (9), that the water saturation of the formation under study can be obtained. To facilitate the use of the method Fig. 4 gives a graphical representation of the three equations.

To obtain the water saturation, the value of the S. P. deflection is read on the ordinate axis, the intersection of that value with the oblique line corresponding to the value of R_i/R_t is determined; the abscissa of the intersection represents the water saturation in per cent.

Calculation of the Porosity

From equation (1), it is easy to see that when R_t, R_w, and S are known, the formation factor F can be readily calculated.

When F is calculated, the porosity can be determined if one knows the value of the cementation factor "m".

Fig. 5 permits the calculation of the porosity by taking S the water saturation as abscissa and R_t/R_w as ordinate. The intersection falls on an oblique line representing the porosity in per cent. The oblique solid lines are for loose formations, and the dashed lines are for consolidated formations of low porosity.

The values of the cementation factor taken for the calculation were selected from experimental data secured in various fields of the Rocky Mountains. It has been found that the value of the porosity affects the value of "m" as indicated by the tabulated figures at the upper left of Fig. 5.

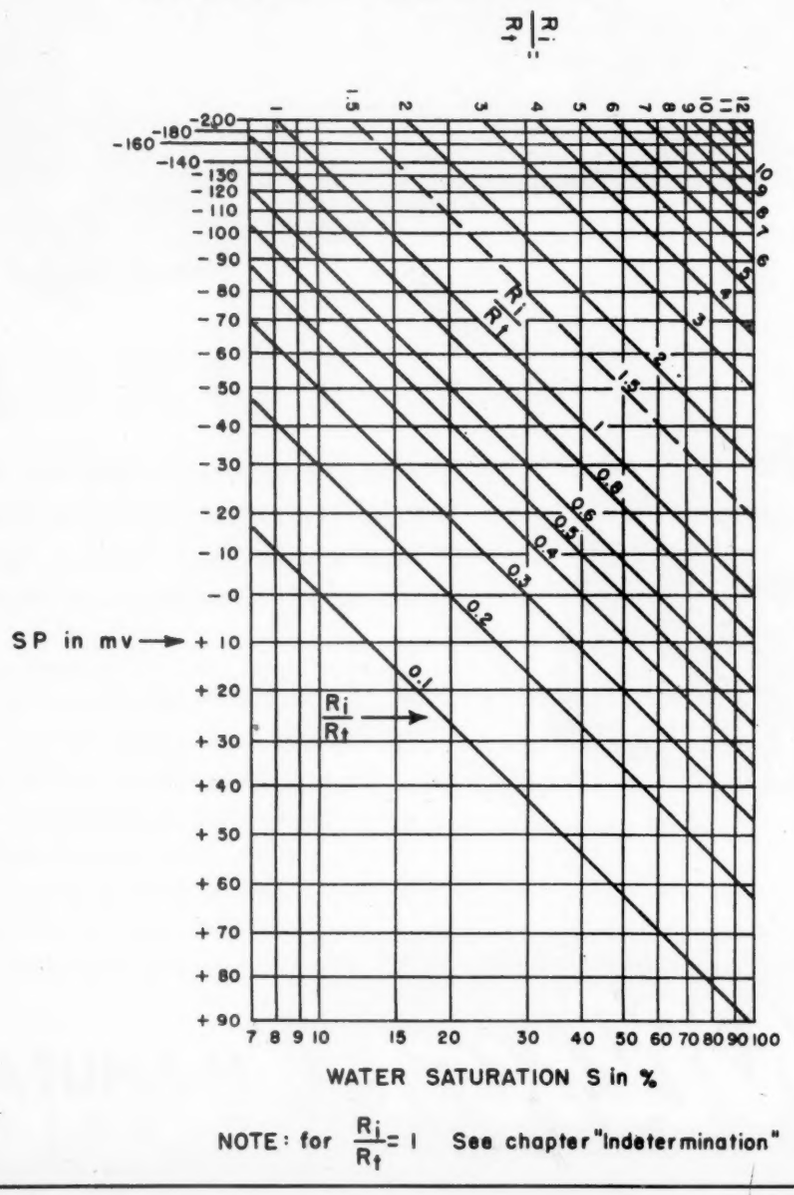
Indetermination

The resistivity of the invaded zone R_i sometimes happens to be substantially equal to the resistivity of the formation ($R_i/R_t = 1$). Two solutions are then possible:

(1) *The formation is permeable*, and the ratio $\frac{R_i}{R_t} = 1$ is just a coincidence. It means that the mixture of the various fluids in the invaded zone (mud, formation water, hydrocarbons) occurs in such amounts as to give the invaded zone the same resistivity value as the unaltered formation. Thus, when $\frac{R_i}{R_t} = 1$ is accompanied by an appreciable S. P. value. the formation is usually well saturated with hydrocarbons; and this method of analysis can be used.

(2) *The formation has no permeability*, and no invasion has occurred. Since the analysis is based on the presence of invasion, it will give ridiculous results when applied in this case. Fortunately, in most formations, and par-

FIG. 4. Calculation of water saturation S.



*M. R. J. Wyllie, "A Quantitative Analysis of the Electro-chemical Component of the S. P. Curve" (AIME, T. P. No. 2511—Petroleum Technology, January, 1949).
M. R. J. Wyllie, "A Statistical Study of the Accuracy of Some Connate Water Resistivity Determination Made From S. P. Log Data" (AAPG Meeting, St. Louis, March, 1949).

ticularly in the Tertiary Series, no S. P. deflection is observed when the formation has no permeability. In this case, it can be seen from Fig. 4 that a water saturation of 100 per cent will be obtained if the method is used. this means that all the water present in the formation is connate. In older formations, S. P. deflections are sometimes observed opposite formations with no permeability. If this method is used, the water saturation found may be relatively low, and would infer that the remaining fraction of the voids is filled with hydrocarbons. This is, of course, impossible since no oil migration takes place in formations with no permeability.

Usually, local experience permits classifying the indetermination as Type 1 or Type 2. In cases where nothing is known, the indetermination can be classified by remaking the electric log with a new mud quite different in resistivity from the original mud. If the formation is permeable, the new invasion will sufficiently affect the resistivity of the invaded zone to give a ratio $\frac{R_i}{R_t}$ different from one. On the contrary, if the formation has no permeability, the ratio $\frac{R_i}{R_t}$ will be one regardless of the resistivity of the mud.

Critical Water Saturations

It is well known that the water saturation in a given formation is a function of:

(a) The distribution of the voids and permeability of the formation.

(b) The capillary pressure existing at that level between the reservoir fluid and water phases. This capillary pressure will vary with the height above the level of 100 per cent water saturation, and with the difference in density between the water and the reservoir fluid.

In the Rocky Mountains with low permeabilities and heavy oil, transition zones have been observed to be quite thick. This means that many structures with small relief do not present commercial interest when black, heavy oils are anticipated.

Fig. 6, curve "A", shows how the water saturation varies with the permeability for an oil saturated sandstone. This curve was obtained in a laboratory, using a fairly high level of capillary pressure. Curve "B" shows the saturation for that sandstone for which a water cut is likely to be produced with the oil, initially or a short time after, the start of production. Charts of this type can be constructed for other geological horizons.

It can easily be seen that water

FIG. 5.

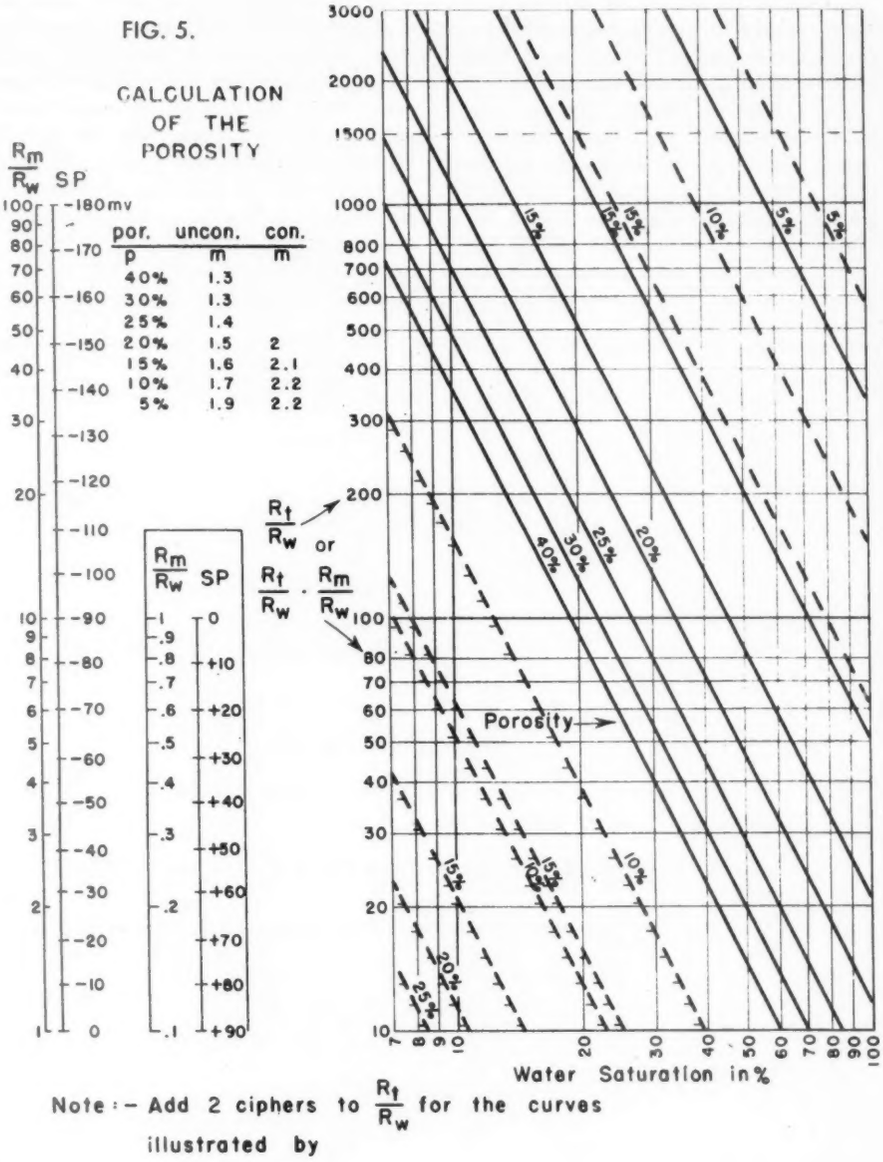
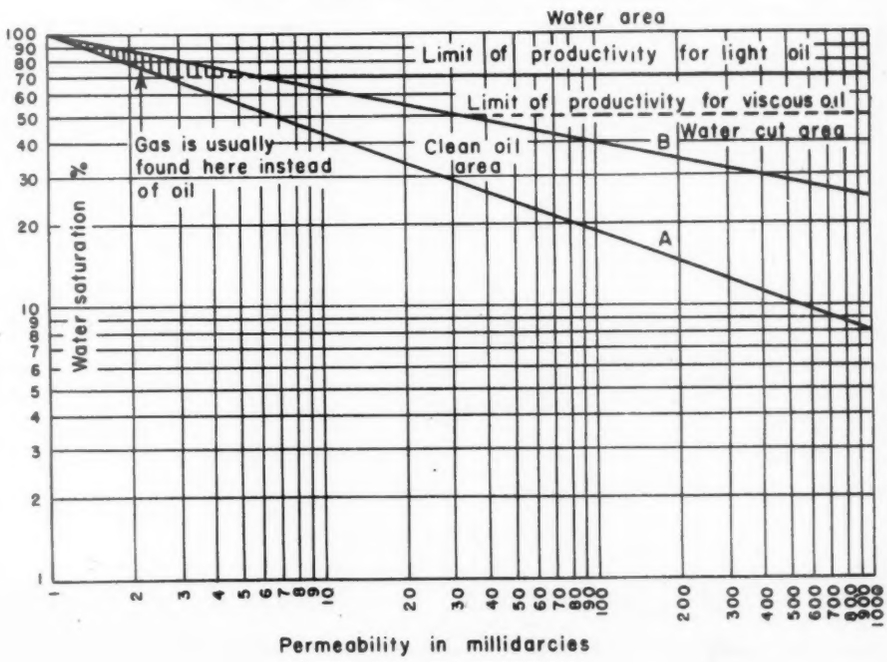


FIG. 6. Water saturation vs. permeability



saturations in excess of 40 per cent correspond to very low permeabilities, to depleted reservoirs, or to a level near to or in the transition zone.

As a rule of thumb, 70 per cent water saturation is given as the economic limit for the light oils of the Rocky Mountains; and 50 per cent water saturation as the limit for highly viscous low gravity oils. It has been found that gas production can occur with very low permeability.

In limestones, a low water saturation is necessary for clean oil production. Well saturated limestones have a water saturation lower than 15 per cent. When the calculated water saturation exceeds 25 per cent, the possibility of production is practically nil. Relation (5) is not too accurate in limestones, and may result in too optimistic determinations.

In depleted sands, this method also gives too optimistic results, because the oil displacement in the invaded zone is greater than indicated by relation (5). For this reason, it must be remembered that the water saturation in depleted sands is always larger than that calculated by this method.

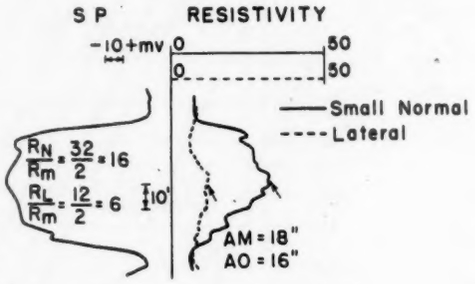
Typical Electric Logs in the Rocky Mountains

Figs. 7 and 8 show a few examples of applications of the method to electrical logs.

Fig. 7 (a)

EXAMPLE 1

OIL SAND



R_m = 2.00 ohms at 122° F hole size 9"

$\frac{R_i}{R_m}$ = 14 $\frac{R_i}{R_t}=\frac{14}{6}$ = 2.33 SP = -90 mv

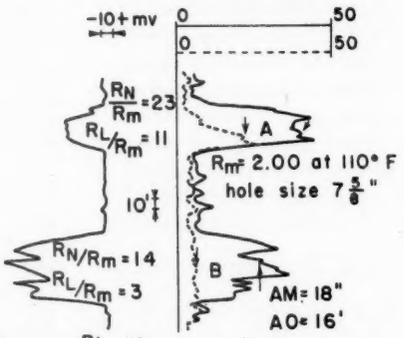
S = 38%

$\frac{R_t}{R_m}$ = 6 $\frac{R_t}{R_w}$ = 6 x 10 = 60 P = 23%

Fig. 7 (b)

EXAMPLE 2

WATER SANDS



A) $\frac{R_i}{R_m}$ = 19 $\frac{R_i}{R_t}=\frac{19}{11}$ = 1.72 SP = -25 mv

S = 100%

$\frac{R_t}{R_m}$ = 11 $\frac{R_t}{R_w}$ = 11 x 1.9 = 20.9 P = 15%

B) $\frac{R_i}{R_m}$ = 12 $\frac{R_i}{R_t}=\frac{12}{3}$ = 4 SP = -65 mv

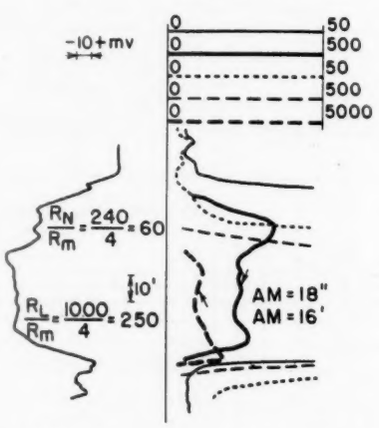
S = 100%

$\frac{R_t}{R_m}$ = 3 $\frac{R_t}{R_w}$ = 3 x 5.3 P = 18%

Fig. 7(c)

EXAMPLE 3

SANDSTONE (OIL and GAS)



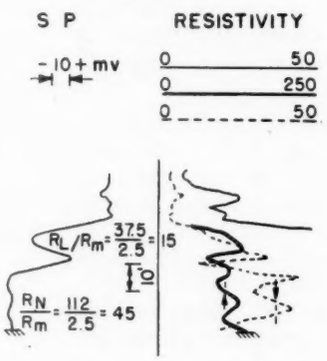
R_m = 4.00 ohms at 120° F hole size 9"

$\frac{R_i}{R_m}$ = 74 $\frac{R_i}{R_t}=\frac{74}{175}$ = 0.425 SP = -70 mv

S = 10%

$\frac{R_t}{R_m}$ = 175 $\frac{R_t}{R_w}$ = 175 x 6 = 1050 P = 21%

Fig. 7 (d)



R_m = 2.5 at 122° F HOLE SIZE 9"

$\frac{R_i}{R_m}$ = 48 $\frac{R_i}{R_t}=\frac{48}{14}$ = 3.4 SP = -65 mv

S = 86 %

$\frac{R_t}{R_m}$ = 14 $\frac{R_t}{R_w}$ = 14 x 5.3 = 74 p = 15%. (con)

EXAMPLE 4

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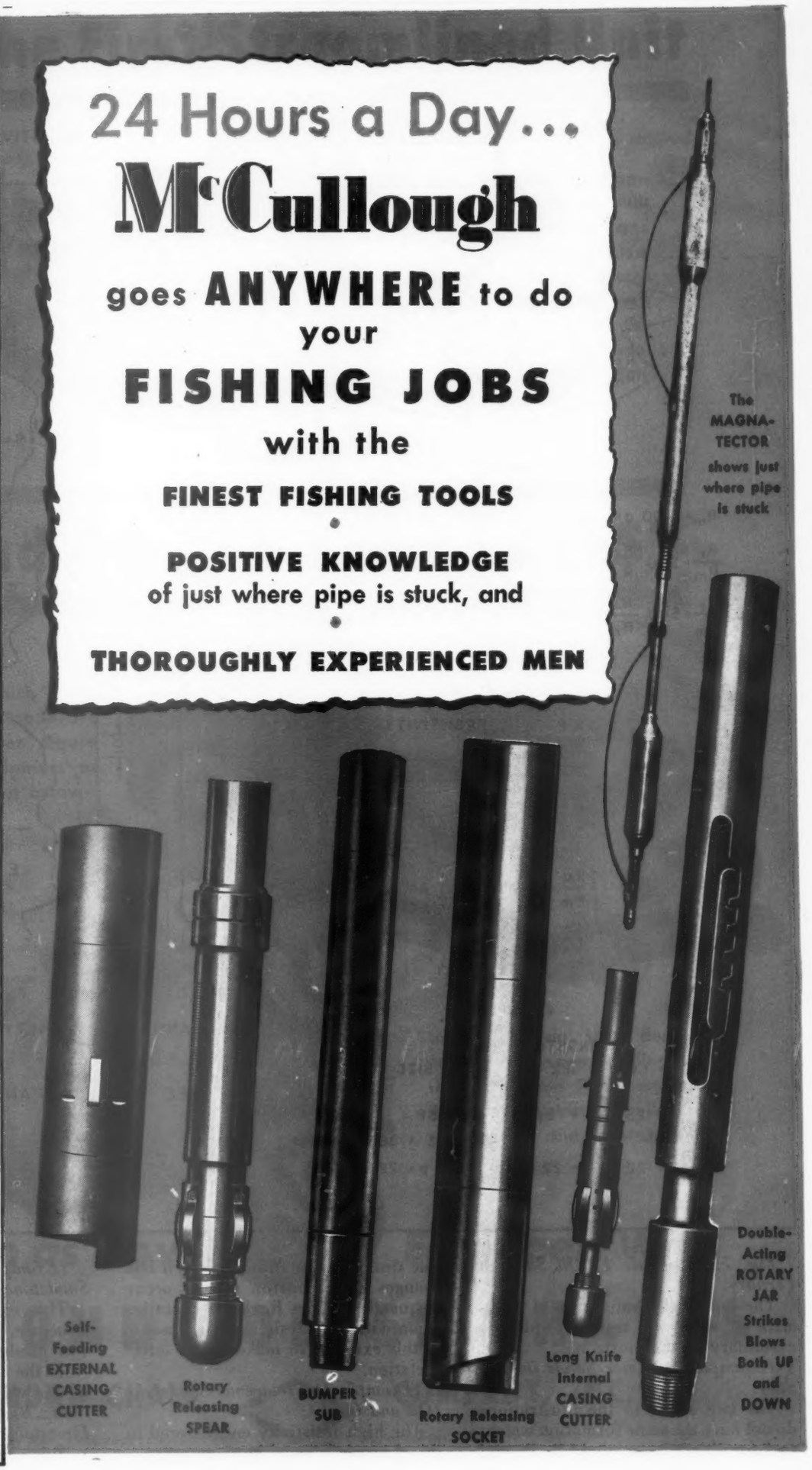
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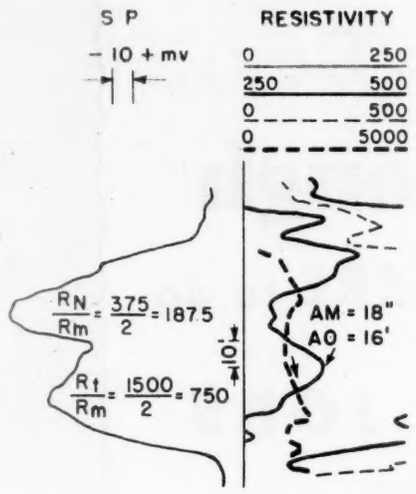
Fig. 8



EXAMPLE 5

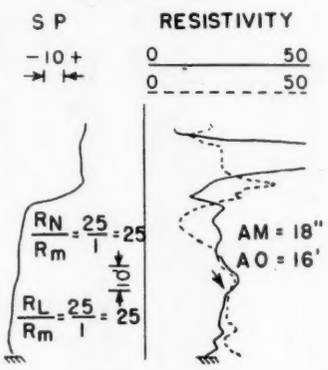
LIMESTONE (OIL and GAS)

R_m = 2.00 at 200° F HOLE SIZE 8 1/2

$\frac{R_i}{R_m}$ = 540 $\frac{R_i}{R_t}$ = 1 app. SP = −125 mv (max.)

$\frac{R_t}{R_m}$ = 540 $\frac{R_t}{R_m}$ = 520 x 24.5 = 12800 p = 10% (cons)

Fig. 8 (a)



EXAMPLE 6

SANDSTONE (OIL)

R_m = 1.00 at 122° F HOLE SIZE 9"

$\frac{R_i}{R_m}$ = 23 $\frac{R_i}{R_t}$ = 1 app. SP = − 45 mv

S = 36%

$\frac{R_t}{R_m}$ = 22 $\frac{R_t}{R_m}$ = 22 x 3.2 = 70.4 p = 22%

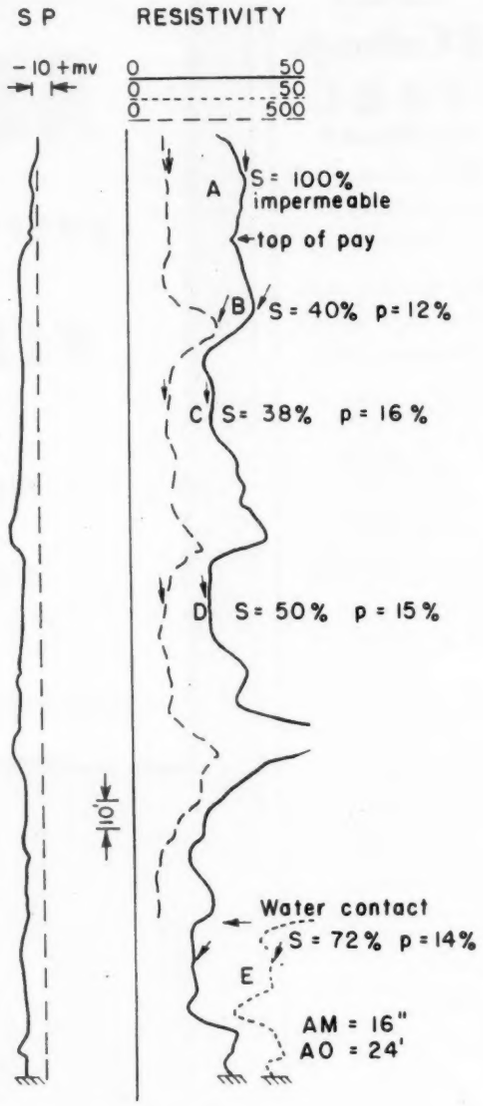


Fig. 8 (b) EXAMPLE 7

SANDSTONE (SALTY MUD)

R = 0.25 at 150° F HOLE SIZE 9"

SEE TEXT FOR ANALYSIS

Fig. 7: (Example 1) Oil Sand in Tertiary.

The high water saturation is indicative of small oil reserve, which is customary in this horizon.

(Example 2) Water Sands in Tertiary.

The two sands in the illustrations do not have the same formation water; and for this reason, their S. P. and true resistivity are different. Such fast changes in formation waters occur frequently in the Rocky Mountains. Quantitative analysis is indispensable in this example to make a true interpretation.

(Example 3) Cretaceous Sandstone (Oil and Gas).

The high resistivity encountered in this example is usual in many areas.

(Example 4) Water in Cretaceous Sandstones.

This example shows a sand off-structure, where nothing but water was produced at the level indicated. Note the fairly high resistivity value in this water-bearing sandstone.

Fig. 8: (Example 5) Oil and Gas in Limestone.

This example shows hydrocarbon

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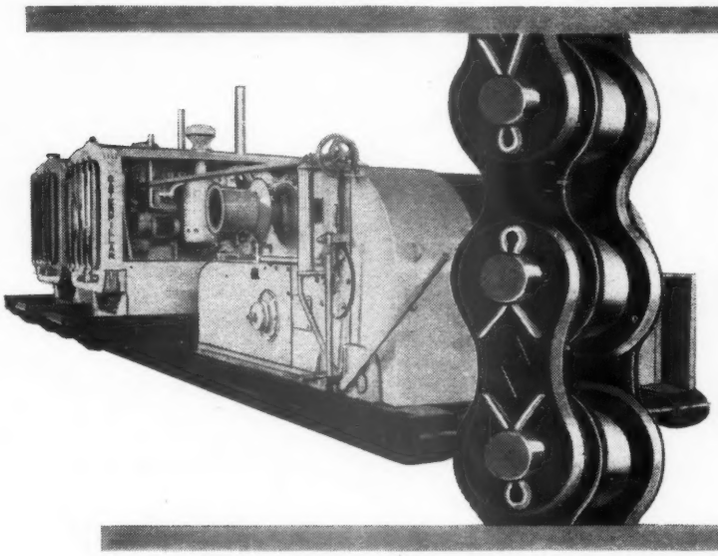

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saturation in the Permian limestone. The ratio $R_i/R_t = 1$; and, consequently, this is an indetermination. Local knowledge permitted to solve the problem, although the example is taken from a wildcat.

(Example 6) Jurassic Sandstone (oil).

The ratio $R_i/R_t = 1$, and this also could be an indetermination. Fortunately, other levels in the sand show that invasion takes place because R_i/R_t is not always equal to unity.

(Example 7) Pennsylvanian Sandstone Surveyed with Salty Mud.

This example is particularly interesting because of the salty mud at the time of the survy (.25 @ 150 F). Little S. P. is seen opposite the formations illustrated. A detailed analysis of the example is as follows:

Level A:

$$R_N/R_m = \frac{31}{0.25} = 124$$

$$R_L/R_m = \frac{110}{0.25} = 440$$

$$R_i/R_t = 1$$
$$R_i/R_m = 250$$
$$R_t/R_m = 250$$
$$SP = 0$$

This is an indetermination, and the formation may be impermeable. If the method is used, a water saturation of 100 per cent and porosity of 8 per cent (consolidated), will result. Obviously, no hydrocarbon saturation is present. This interval is actually above the pay and represents a hard formation.

Level B:

$$R_N/R_m = \frac{35}{0.25} = 140$$

$$R_L/R_m = \frac{250}{0.25} = 1000$$

$$R_i/R_t = .55$$
$$R_i/R_m = 285$$
$$R_t/R_m = 520$$
$$SP = -15 \text{ mv (max)}$$
$$S = 40\%$$
$$p = 12\% \text{ (consolidated)}$$

This level is actually in the pay section, although a rather small porosity is found. The top of the pay, as shown in the example, is not too easy to see except for a small variation in the S. P. curve. Level A and level B could be distinguished only by means of quantitative analysis.

Level C:

$$R_N/R_m = \frac{21}{0.25} = 84$$

$$R_L/R_m = \frac{100}{0.25} = 400$$

$$R_i/R_t = .52$$
$$R_i/R_m = 130$$
$$R_t/R_m = 250$$

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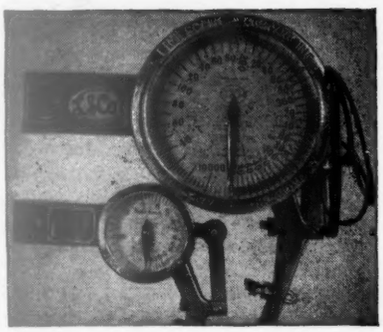

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SP = —15 mv (max)
S = 38%
p = 16% (consolidated)

This is the best part of the pay.

Level D:

$$R_N/R_m = \frac{21}{0.25} = 84$$

$$R_L/R_m = \frac{80}{0.25} = 320$$

R_i/R_t = .7
R_i/R_m = 135
R_t/R_m = 190
SP = —15 mv (max)
S = 50%
p = 15% (consolidated)

This level is still in the pay, but a higher water saturation is already seen.

Level E:

R_N/R_m = 17 = 68

$$R_L/R_m = \frac{37}{0.25} = 148$$

R_i/R_t = 1
R_i/R_m = 96
R_t/R_m = 96
SP = —15 mv (max)

This could be an indetermination. The method would give S = 72% p = 14% (consolidated). In any case, this level is not a part of the pay because, if permeable, the water saturation is too high. It is most likely that this level is in the transition zone, and will produce mostly water.

It is interesting to see the increase in water saturation with depth. The porous zones in the sandstone are shown by relatively low values in resistivity; and the hard tight zones, by high values of resistivity. the water contact is likely to be at the top of the zone from which level E was taken for calculation.

Conclusion

The above method is based upon different assumptions, such as the hypothesis making possible the determination of $\frac{R_z}{R_w}$, approximate evaluation of R_i/R_m and R_t/R_m, and preliminary obseravtions which have shown that parameters such as S and Si, deduced from electrical logs in the area under study, can be related to each other by a simple equation.

Other observations have also permitted the determination of an average value of coefficient K which appears in the equation relating the S. P. deflections to the ratio $\frac{R_m}{R_w}$.

An essential feature of the method is that the parameters deduced from electrical logs appear in equation (6) in the form of ratios $\frac{R_i}{R_t}$, $\frac{R_m}{R_w}$; which decreases the influence of the errors implied in the determination of each parameter. R_i and R_t are, for instance, deduced from apparent resistivities, measured with short and long devices, which are both influenced by hole diameter, mud resistivity, bed thickness, etc. This influence, although it is not the same for each device, gives rise to errors in the value of R_i and R_t which partially compensate each other when the ratio $\frac{R_i}{R_t}$ is the one taken into consideration.

Also the ratio $\frac{R_m}{R_w}$, deduced from the value of the S. P. deflection, is independent of any possible error concerning the measurement of R_m. Moreover, $\frac{R_m}{R_w}$ is generally small in the Rocky Mountains, and is comparatively little affected by an error in the value of coefficient K.

The method has thus led to numerous evaluations of water saturation and porosity in the Rocky Mountains which have been checked and which, on the average, have appeared quite reliable.

Acknowledgment

The author wishes to acknowledge the cooperation of the California Company, Mountain Fuel Supply Company, Pure Oil Company and Sinclair Wyoming Oil Company which were kind enough to provide examples. He also wishes to express appreciation to R. Sauvage, R. C. Davis, and M. Martin for their help in the preparation of the manuscript.

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GEOPHYSICAL EXPLORATION*

R. D. WYCKOFF†

Abstract

This paper covers, in a non-technical manner, the geophysical equipment currently available to meet the diverse problems encountered in present-day petroleum exploration. Innovations in operational techniques developed to meet the specialized needs of over-water exploration are discussed briefly, with special emphasis on radio-location methods. The importance of the drilling phase of exploration is stressed, with the reminder that in the Gulf of Mexico this alone will determine the efficacy and extent of the exploratory work in this important province.

I. INTRODUCTION

It has been said that the continuous and persevering search for oil that has characterized our petroleum industry has been the most important factor in maintaining our reserves. I think no one will contest the statement that in this perseverance the American petroleum industry has led the world. It has led not only in the scope and sheer magnitude of operations, but in the development and perfection of exploration tools—both geological and geophysical. These facts are amply substantiated by the already established record of the industry, both at home and abroad.

But if the record in the past has been one of diligence, that of the future must be even more persevering. For, if the postwar era has marked any change, it is that for the first time in two decades we seem to have emerged from a period marked by surpluses to a condition of tension between supply and demand. Thus there has developed the urgent need to expand our petroleum-producing areas into every potentially productive region within reach of the drill. These new circumstances, as is always the case when new economic forces create new frontiers, have resulted in a remarkably rapid expansion of exploration into hitherto neglected provinces; and, with this change, new problems have come to those responsible for exploration.

Particularly noteworthy is the added responsibility being placed on geophysics in the preliminary phases of geological evaluation of virgin areas. Greater use is being made of the potentialities of geophysical reconnaissance methods, followed directly by detailing and the drill. This has not been a sudden development; but the growing trend, brought about by the very nature of the new areas under scrutiny, does seem to have crystallized into a generally accepted policy. Indeed, already in some new provinces, this has been the pattern of exploratory operations that have met with success. It is certain to be the pattern as available territory becomes more and more inaccessible to surface geological exploration.

In addition to the demand for better geophysical reconnaissance, these same circumstances inevitably call for better resolving power in our detailing tools. The enormously expanding costs of far-flung foreign operations and the hazards and problems of drilling in difficult terrain or water operations do, for economic reasons alone, require greater certainty in the delineation of promising structures.

I need not remind you that the postwar era has brought out no new geophysical *methods*. Except perhaps in very special cases, petroleum exploration still places its principal reliance on the three basic methods, viz., magnetic, gravimetric, and seismic measurements. There have been improvements in instrumentation for all three methods. There has been a gradual but very definite improvement in interpretation techniques in all three methods, brought about by cumulative experience and, to no small degree, by the stimulation afforded interpretation personnel through the evident increased confidence of the industry in the work of this personnel. New auxiliary tools and some unique operational methods have been developed to meet the greatly diversified physical conditions encountered in the expanded scope of operations.

Without going into details which would be of interest primarily to geophysicists, it is the purpose of this discussion to review briefly how available methods and auxiliary tools are being used in current exploration programs. I shall of necessity consider the continental shelf province of Texas and Louisiana as merely one example and, geophysically speaking, a rather simple problem among the many new ones confronting the industry. For this reason, I believe it will be more profitable herein to outline briefly the application of the three basic methods in broad exploration programs of the prevalently occurring type and, in passing, to point out the present state of instrumentation and certain new operational techniques and equipment that of necessity have become a part of the geophysicist's equipment.

II. GEOPHYSICAL RECONNAISSANCE

The use of magnetic or gravimetric measurements in geophysical exploration was introduced initially with the sole view of exploiting their capabilities in locating or even detailing certain types of structures. Thus the use of gravity measurements for direct finding of salt domes, and even to detail them, is too well-known to require comment. Similarly, but perhaps less spectacularly, is the case of magnetic measurements for igneous intrusions and other structural types involving the relatively highly magnetic basement rocks. Fortunately both the nature of the observations and instrumental improvements permit the survey of large areas at reasonably low cost. As a result, both magnetic and gravity surveys are now generally considered as available reconnaissance methods. This is particularly true because accumulated experience and advances in interpretation have served to emphasize certain inherent features adaptable to such applications. However, first let me emphasize that by reconnaissance I do not mean mere coverage of large areas for the sole purpose of stumbling upon structural details. Rather I refer to its use with the view of determining regional geological features where direct geologi-

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†Gulf Research and Development Company, Pittsburgh, Pennsylvania.

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cal examination is impractical as, for example, some water-covered areas. On the other hand, such an area as the Gulf Coast continental shelf is a part of a well explored province, and the problem there is primarily one of finding local structure. Thus a regional gravity survey quite capable of locating salt domes directly would not be reconnaissance within the present meaning.

As is well-known, in a virgin province there are broad basic geological questions that are of importance as well as the detailed structural configuration, and in this rôle magnetic and gravity surveys are useful, even though any hoped-for indication of local structure may turn out to be rather nebulous.

Magnetic Surveys

The measurement of the earth's magnetic field comprises the oldest of the three geophysical methods discussed herein. Perhaps this may explain why it was the first to attain the black list of the petroleum industry back in the days when, for some reason, any data which contoured as a "high" were frequently accepted as a structural high and a place to drill. At any rate, the many early failures of magnetics—failures due to misapplication and erroneous interpretation—almost relegated this method to obscurity.

Fortunately, however, we now know that, although basement structure may be reflected in the magnetic map, usually the prominent anomalies arise from discontinuities in the character of the igneous rocks composing the basement, and that they bear no necessary relation to structure. Nevertheless, even such features can be useful to the interpreter; for it is now quite well-known that, by careful study of a regional map, an interpreter can calculate the depth to basement with a fair degree of accuracy. By "fair" is meant not order of magnitude, but in reasonably favorable cases—within 10 per cent and frequently better—as has been proved in rank wildcat territory. Obviously, in virgin areas such information is of basic value and illustrates what is meant by reconnaissance in the pure sense.

When the basement rocks are not too deep, structural features in the basement such as major uplifts, major faults, and structural trends may be disclosed through the obscuring features caused by mere changes in basement composition. In areas of still shallower basement, and where the sediments are conformable, even small features representing promising structure may be found, and the method verges on being a detailing tool. Certainly, however, the magnetic method is admirably suited to its broader field of reconnaissance and, fortunately, instrumentation has proceeded to the point where rapid coverage to suit any conditions and over any type of terrain is now possible.

Magnetic measurements, to be of full value, should have an accuracy of 1 or 2 parts in 50,000—an accuracy of 1 or 2 gamma in geophysical terminology. Such accuracy is possible with proper design and operation of the well-known Schmidt magnetometer which has been used for years in the industry. There is also available an air-borne instrument capable of comparable accuracy, but at the same time equipped with the seven-leagued boots of air transport. Not only does the air-borne feature permit the coverage of 500 to 1000 miles of continuously recorded profile per day with a single instrument, but it permits such surveys unhampered by any terrain problems. Moreover, in areas plagued by very local magnetic disturbances, such as those caused by scattered igneous débris where land instruments are rendered ineffective, the air-borne magnetometer is sufficiently removed from such very local disturbances to eliminate them altogether.

Gravity Surveys

The measurement of the earth's gravitational field is an ancient art which has found broad use in exploration geophysics because of the extreme accuracy possible in the measurement of local variations of gravity. Direct deflecting instruments—i.e., gravimeters—capable of relative measurements within 2 or 3 parts in 100 million have been generally available for more than 10 years. Some very recent instruments are extremely portable and easily carried by one man. Because of their extreme sensitivity, gravity maps based on properly conducted gravimeter surveys reflect geological features involving variations in density distribution in *both* the basement and the sedimentary rocks. As in the case of magnetics, large regional gravity anomalies are observed which have their source deep within the basement and which may bear no relation to structure. On the other hand, unlike magnetics which are relatively insensitive to normal sedimentary rocks, gravitational anomalies can arise from density variations in the sedimentary section. Hence, there are areas where gravity reconnaissance may be more diagnostic than magnetics, although this may not be predictable beforehand.

Again, as in the case of magnetics, because of the nature of the observations and the extremely portable instruments of recent development, the method is well suited to reconnaissance; and, depending on the geology of the province, it may be better suited than magnetics as a means of high-grading large areas for subsequent detailing. This is a question best answered by actual trial.

The question immediately arises as to the possibility of developing a gravimeter for use in aircraft for the purpose of increasing operational speeds as in the case of magnetics. It should be pointed out that gravity measurements are measurements of gravitational acceleration, and there is no way to separate motional and gravitational accelerations; and it is obviously impossible to fly any aircraft in a perfectly straight line and at such constant speed as to eliminate motional accelerations within the precision required in gravitational surveys. An air-borne gravimeter for exploration can, therefore, almost certainly be relegated to the realm of the impracticable.

It is also of interest to mention here that most modern gravimeters have such high sensitivity that they are already capable of measurements below the "noise level" of practical operation; i.e., disturbances due to local unknown density inhomogeneities, as well as errors in the determination of the elevation of the point of observation, exceed the observational accuracy of the modern instruments. Thus, new instrument design aims for greater portability and ease of manipulation rather than increased sensitivity.

To meet the need for under-water operations, such as in the Gulf of Mexico, two methods are in use. Inasmuch as a solid foundation is required to eliminate any motional accelerations of the instrument, it must be rested on bottom. Special tripods have been used in water up to 20 ft in depth. More recently, for deeper water, diving bells are used. These are large enough to permit the lowering of both instrument and operator to the bottom where the instrument is then manually leveled and operated as in the case of normal land surveys. Careful design of the bell is required to provide for the safety of the operator. Alternatively, instruments are available which comprise a gravimeter mounted in a pressure-tight case which alone is lowered to the bottom. The instrument is equipped with suitable remote electrical level indicators and level adjustments so that an operator comfortably located on the boat can make the necessary adjustments. When level, the in-

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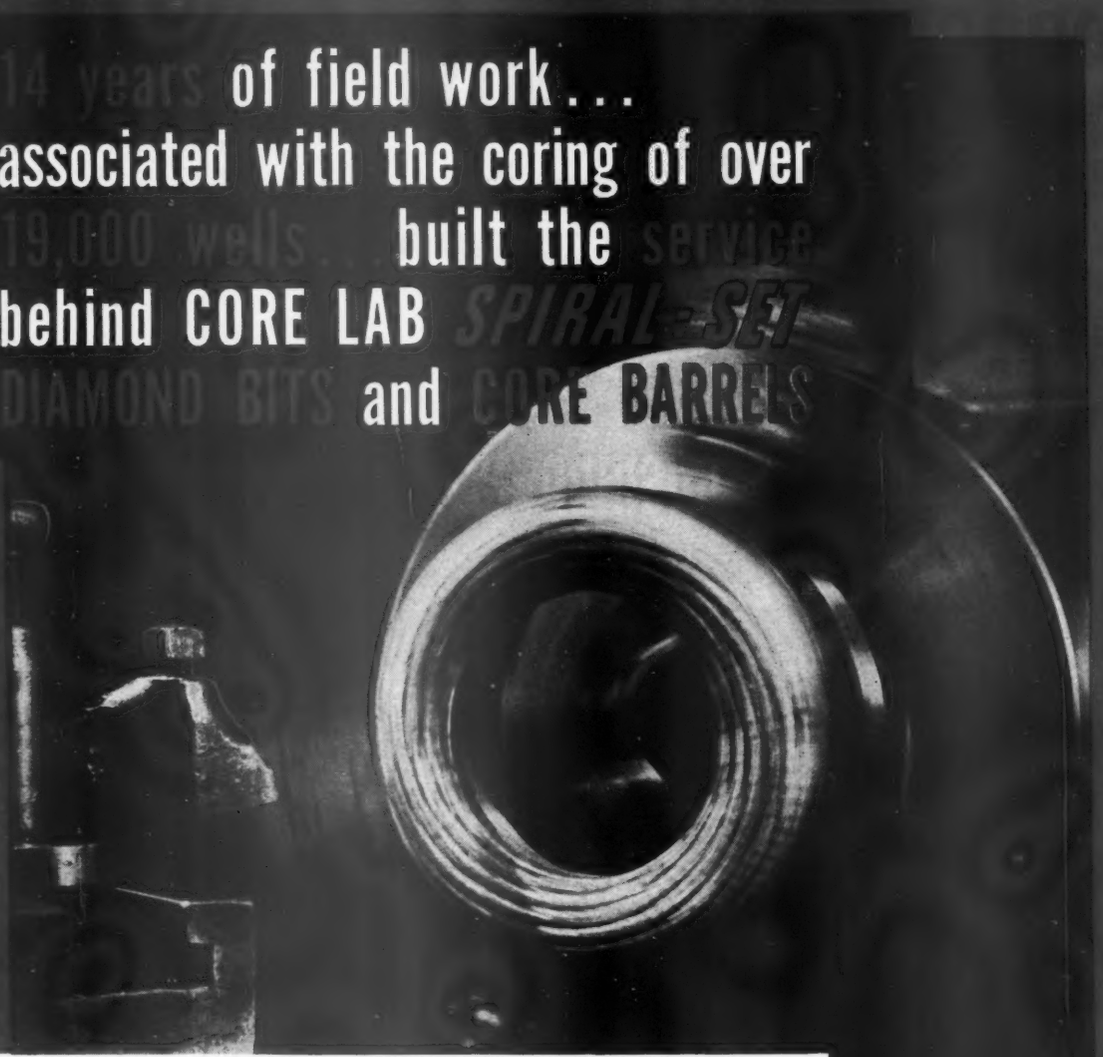

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strument is unclamped by remote control, and a camera photographs the gravimeter reading and codes the record for future identification. Evidently such operation involves smaller equipment than the man-carrying diving bell, and the size of boat required is then determined largely by safety and speed requirements. Speed is important because a major portion of the time consumed in water surveys of this type involves transportation alone.

It is interesting to note here that gravity instrumentation is now so far advanced that, in a normal land survey of high precision, about two-thirds of the total cost involves the surveying—primarily elevations—which should be accurate to within about 0.5 ft. Thus there is more to be gained by the development of rapid level survey methods than by improvement of the gravimeter itself. Such developments are under way, and some success has already been attained. On the other hand, in the case of water work, the determination of instrument elevation is less troublesome than the location survey, because the water level may be used as the bench mark, and depth to the instrument can be measured by sounding or by a suitable pressure indicator.

Seismograph Surveys

Both the magnetic and gravimetric methods involve the measurement of forces at a distance, and are thus rather indirect methods of determining structural configuration. For this reason, except in very special cases, there must always remain some more or less considerable ambiguity in interpreting the data in terms of geological structure. On the other hand, seismic observations are based on recordings of sound waves which, projected from the near surface, actually reach down and touch or traverse the rock strata. In a sense, we are actually probing the subsurface with the seismograph method, and thus we closely approach our normal concepts of what a detailing tool should do.

Because of complexity of the subsurface, the interpretation of the data is not quite so simple as the probe analogy implies, and only in exceptional cases is the method free of ambiguity. Moreover, it is unfortunate that the wave length of our probe is long, because short waves are highly attenuated in the earth and soon fade to the vanishing point. These long waves are somewhat analogous to the use of a measuring stick with an elastic tip, i.e., it limits the resolution of the device to an embarrassing but unavoidable degree in the case of very

complex structure. However, we are not interested here in technical details. They are mentioned merely to indicate why instrumentation of the seismograph is severely limited as compared to some of the wartime acoustic devices of which we have heard, and which perhaps we have assumed might appear eventually in some form in seismograph equipment.

You are no doubt familiar with the use of refraction, or even reflection, work in what has sometimes been called reconnaissance work. You are well aware of the previous use of refraction work in the location of salt domes, but perhaps you are less aware that refraction shooting has become increasingly important as a detailing tool when reflection work is difficult or even impossible. It is not fitting here to go into detail concerning the relative merits of these methods under various conditions, but merely to point out that either or both may be used in the final stages of an exploration program. In any event, whether reflection or refraction methods are used, the problems involved in field operations over difficult terrain or water work are essentially the same, and need no separate discussion.

It is pertinent, however, to point out here that, once the special facilities required for water operations have been provided and necessary experience has been attained, such operations usually proceed more rapidly and with greater facility than is the case in much of our land operations. Thus, because of the speed of the work, it is found more practical in the Gulf of Mexico to use continuous reflection profiling methods, rather than the older refraction techniques—even in the search for shallow salt domes—with the obvious advantage of securing incomparably greater detail in subsurface data, including minor features when the profiling is done with sufficiently close spacing. Moreover, it is of interest to add that, in the work in the Gulf of Mexico, better seismograph records are available than is the case in adjacent swamp areas; so that an additional degree of certainty attends the exploration in these waters.

III. RADIO SURVEYING

The extension of exploration from near shore to wide expanses of open water, such as the Gulf of Mexico, the Bahamas area, or even Lake Maracaibo, has introduced new problems in surveying. As work drifted farther and farther offshore, the use of orthodox triangulation and chaining methods, using wire line a mile or more long, met with obvious obstacles. At large distances such methods became too cumbersome to keep pace with the operations they are intended to guide. Buoys cannot be maintained with any certainty, and the expansion seaward of a triangulation network by such methods introduces intolerable errors. Moreover, it is desired to know the position of a continuously mobile craft at any time, and even manual surveying methods are not adapted to such operation.

A similar and even more immediate problem is encountered in air-borne magnetometer operations where the position of the aircraft must be known at every instant to within some 50 ft to 100 ft if the required accuracy of the magnetic map is to be attained.

Fortunately, war-born developments have found direct application in meeting the first brunt of this problem, and they represent the only case of a new technique lifted directly from war to geophysical use. For this reason, I shall use a disproportionate amount of time to outline the principles involved. I refer to the use of radio methods for position-finding, wherein the known velocity of radio propagation is used as the measuring stick. The velocity is such that the "echo" of a transmitted signal is returned from a reflector one mile distant in approximately 10 millionths of a second. However, under proper conditions, modern electronic techniques permit the measurement of time intervals to within fractions of a millionth of a second, so that it is now possible to use the travel-time of a radio signal to measure distance to within a relatively few feet in the same manner that the timing of an acoustical echo is sometimes used.

One of the earliest equipments used quite extensively in the Gulf area is radar; and, although it does not represent the most advanced and accurate type of radio-survey equipment, it was immediately available from war surplus, sufficiently compact, and afforded adequate accuracy for much of the near-shore work. Triangulation with this 3-cm and 10-cm radar equipment is effected by the use of corner-reflector targets set up on shore, with extensions seaward through the use of similar target buoys. It might be mentioned that precision angular measurements are not possible with simple radar or other radio equipment, and reliance is placed in distance measurements alone.

A related but more specialized type of equipment, developed during the war, is known as "shoran" (short-range navigation). Here a radio pulse initiated at the mobile station is received at a fixed "transponder" station, where a new pulse is immediately generated and transmitted back to the

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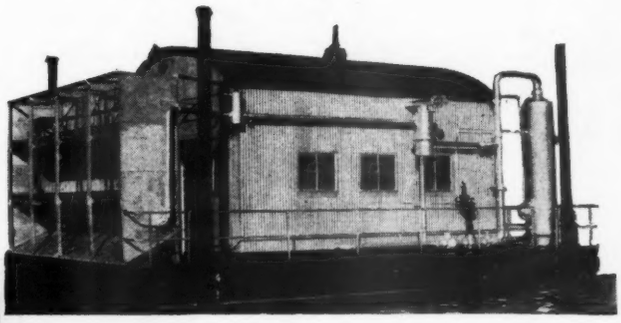

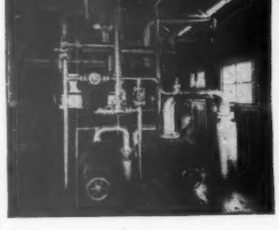

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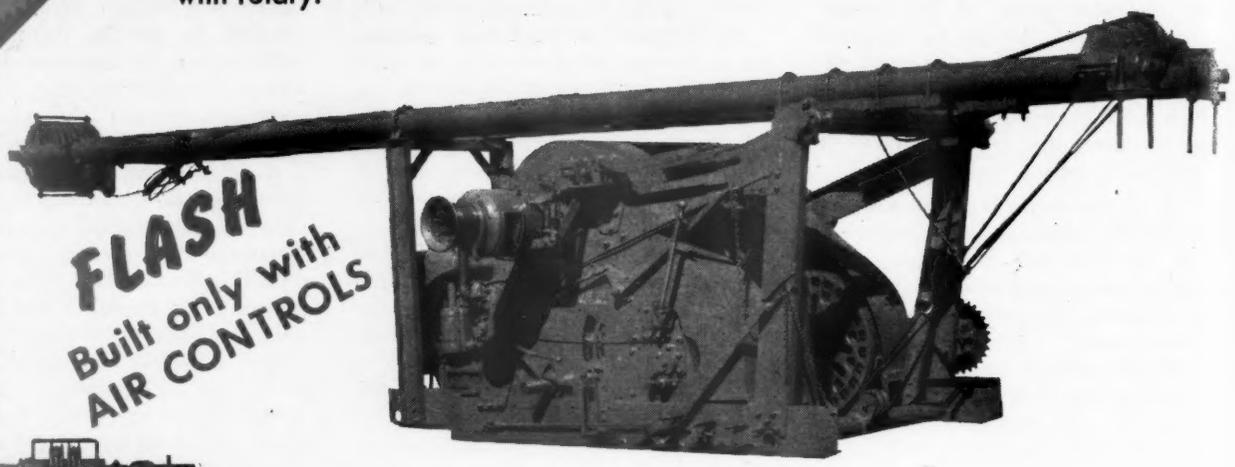

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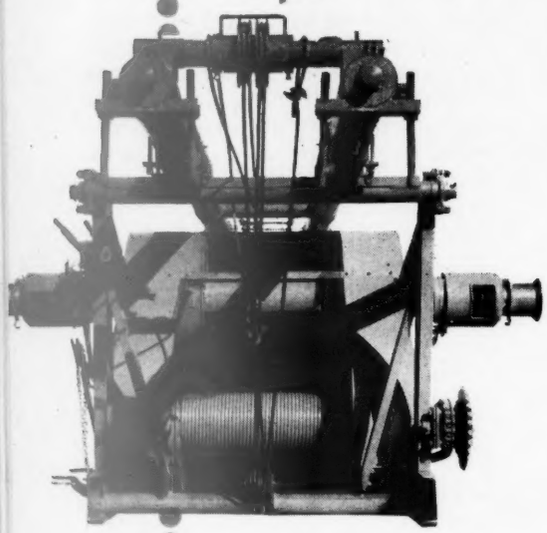

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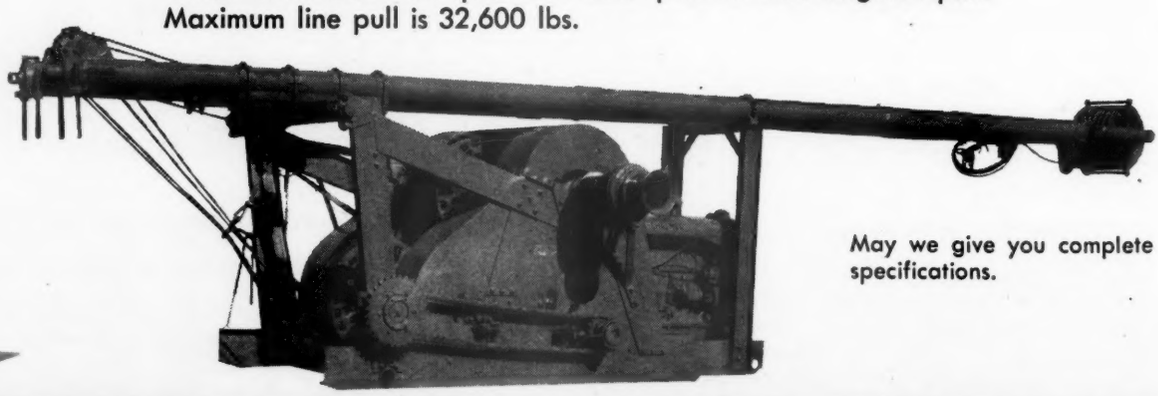

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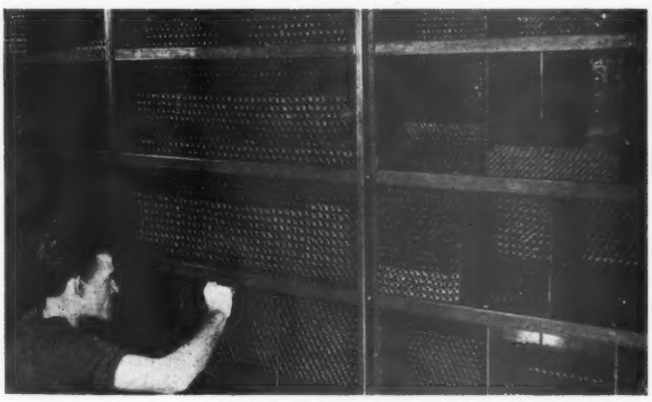
mobile station. The time interval between the initial outgoing pulse and the "pseudo-echo" pulse received from the transponder is measured at the mobile station, and the distance to the fixed transponder location thereby is determined. Time lags within the transponder's repeater equipment are calibrated out in the time-measuring equipment at the mobile station, where the distances are read directly from dials to within about 1/100th mile, or approximately 50 ft. A complete "fix" of the mobile station is obtained at any time by measuring the distance to each of two transponder stations at known locations, as required in any triangulation system. The equipment is so arranged that the interrogation pulses are transmitted at the rate of about 900 per second, and the transmissions are alternated at different frequencies to each of the 2 transponders about every 1/10th second. Thus a continuous stream of distance information is available at the mobile station where, by cathode-ray presentation of the outgoing and incoming pulses, the operator whose duty is to keep the visual pulses on the scope properly matched can continuously "track" his movement with respect to each of the fixed stations—with the distances appearing directly on the tracker dials. In practice, the possible acuracy is found to be within about ± 50 ft.

Clearly, the "shoran" method is analogous to the radar method, but it has a much greater effective range, because the echo pulse is a regenerated one amounting to 10 kw or 15 kw of peak-power instead of a mere vestigial reflection of the original transmission. Moreover, there can be no ambiguity caused by reflections from natural targets, because only the proper transponder will give a response. However, although the potential range of such equipment may be at least 200 miles —with an accuracy independent of distance—it, like radar and other very high-frequency systems, is limited essentially to line-of-sight operations. By this is meant that such high-frequency systems are practically cut off of the horizon in the same manner that an optical path is limited. Hence, the range of radar and shoran systems is definitely limited by the heights of the antenna systems. Using, say, 50-ft masts at both transmitter and target, the line-of-sight range over water would be about 20 miles—and, with 100-ft antennae, it would be extended only to about 28 miles. Obviously, then, the full range capabilities of shoran equipment can be utilized only by aircraft flying at high altitude. In air-borne magnetometer operations, advantage may sometimes be taken of elevated locations for the transponders, and ranges up to 120 miles have actually been used during surveys conducted at an altitude above ground of about 2000 ft.

It is evident that this inherent range limitation, even on radio-survey methods, is a serious handicap in operations which in the Gulf of Mexico will extend to 75 miles or more offshore. Moreover, there is no cure for this limitation in the case of pulse systems of the radar or shoran type which must use high frequencies to generate the sharp pulses demanded by the accuracy requirements. Low-frequency pulse systems, such as "loran," do circumvent the line-of-sight limitation, but to date these long-range navigation systems have inadequate accuracy for exploration work.

Fortunately, there is a radio-survey technique which avoids the use of pulse transmission and which has very high inherent accuracy. It is well adapted to low-frequency operation; in fact, for geophysical operations, it is preferable to operate near or below 2 megacycles where the optical path limitations no longer prevail. These are the so-called phase-comparison



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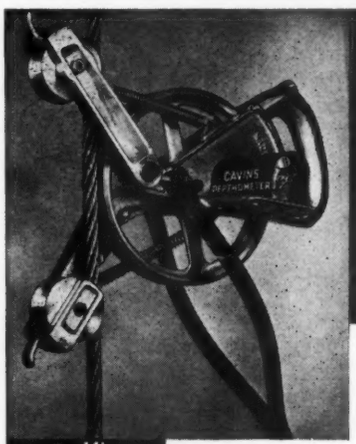

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systems, of which there are numerous embodiments of the same general principle.

Basically, these systems involve the measurement of the phase difference of radio waves received from two continuous-wave transmitters. The radiations from these transmitters produce in space a hyperbolic interference pattern with the transmitters at the foci of the hyperbolas. By the use of two such systems—which provide a grid of two intersecting hyperbolic patterns—a mobile receiver, properly instrumented, is able to chart its motion in space by reference to a map on which this precomputed grid has been drawn. However, unlike the pulse systems which permit a fix to be made at any time, in the phase-comparison systems as now developed, the mobile craft must enter the grid at a known point. Then, by setting the dials to correspond to the position of this point, thereafter the position at any point within the grid is indicated directly on the dials—provided, however, that the equipment has been operating continuously and reliably throughout the interim.

The requirement of entering the survey grid at a known point and of maintaining continuous operation thereafter, together with the need for a precomputed map of the hyperbolic grid for each individual survey network, comprises the most serious drawbacks of phase-comparison systems. On the other hand, at the present time, they offer the only hope for low-frequency operation and, thus, the elimination of the line-of-sight limitations of the radio-pulse methods. One remaining problem is the allocation of frequencies for such use in the already overcrowded low-frequency bands. However, temporary authorization for experimental trial of two such systems in the Gulf of Mexico has recently been given by the Federal Communications Commission.

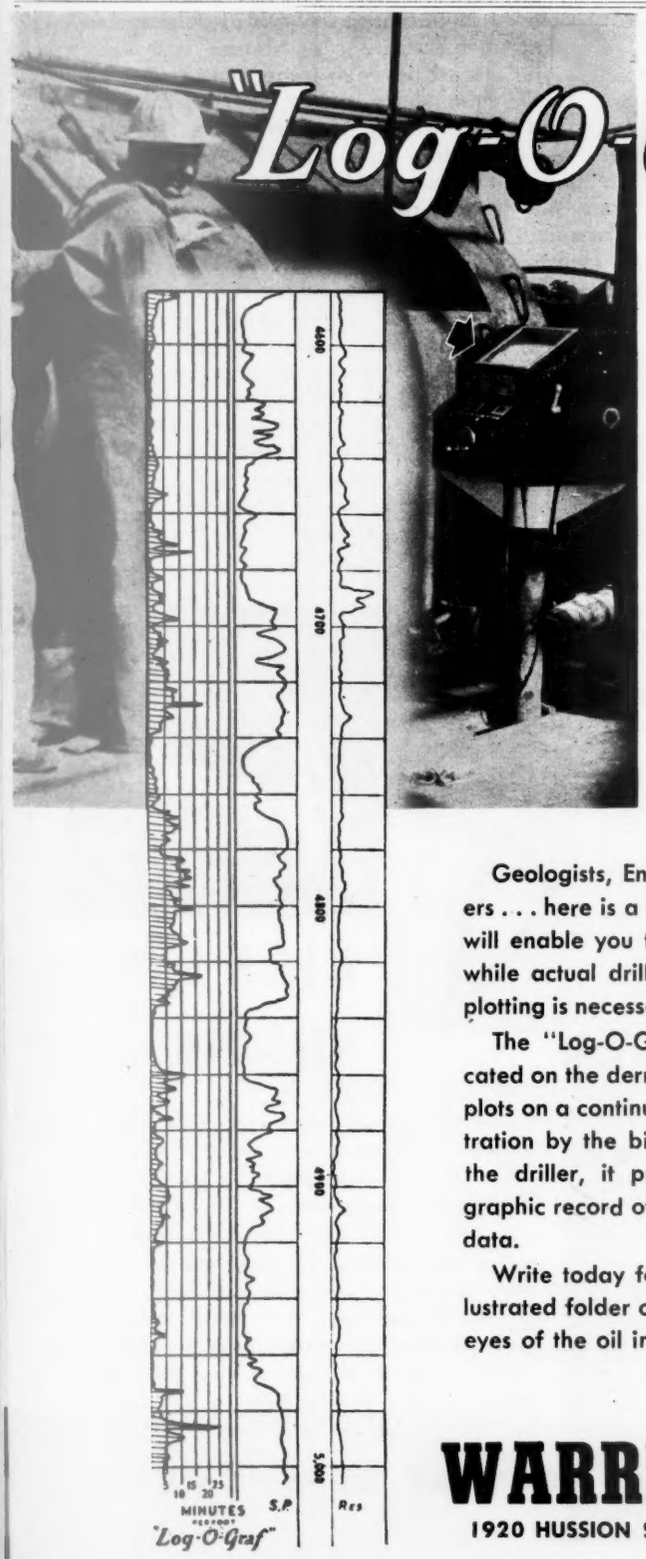
At this early stage of development it is impossible to say what system will prove most useful in geophysical work. However, the use of radio-survey methods has become a necessity, not a mere convenience; and it is likely that all three types, viz., radar, shoran, and phase-comparison equipment, have become permanent additions to our exploration tools. Without them, exploration in many areas would be impractical.

IV. NEW OPERATIONAL TECHNIQUES

We have already considered briefly the status of gravity and magnetic methods as regards new developments. Only in the case of the magnetometer have any revolutionary new instruments or operational techniques been introduced.

In the case of the seismograph, the gradual improvement of the equipment involving modernization of components has occurred. There have been no radical changes. On the other hand, it has been necessary to introduce certain innovations; and these, in particular, are required to meet the diversity of problems encountered in water work. In general, each new province seems to offer its peculiar set of problems—some due to physical characteristics of the sea bottom, and some due to man-made rules and regulations.

One of the first problems encountered in deep-water work was the complexity of the seismic records finally traced to oscillation of the gas bubble formed when the shot was detonated. This introduced obscuring interferences in the character of the reflections recorded. The trouble is eliminated by shooting at a sufficiently



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shallow depth to permit the gas bubble to break the surface. Another shot-point problem is encountered when the bottom comprises such a thick layer of ooze that most of the energy is absorbed before it has a chance to enter the consolidated material. Fortunately this problem generally involves rather localized areas. Except for these and related nuisances, water work in some areas is actually simplified as compared with land operations because of the elimination of shot-hole drilling and the possibility of almost continual motion of the shooter's boat with only a position-spotting problem with which to contend.

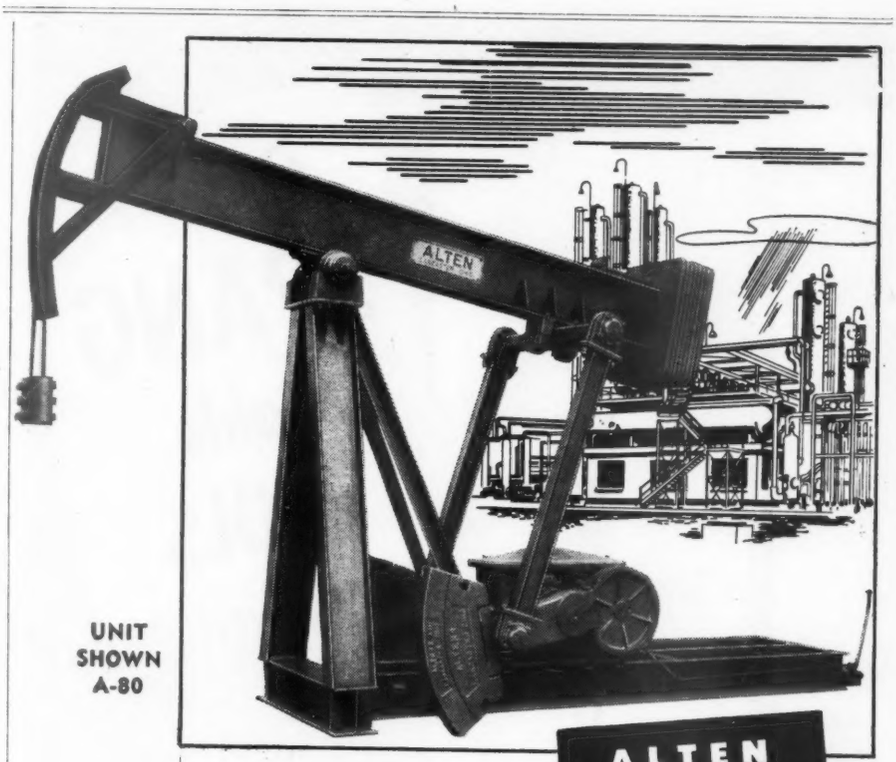
The heart of the seismograph is the detector setup. It is common practice in water work to use the same type of detector or geophone that has been used on land. Obviously, the housing must be modified for marine use; and in many cases, as when the units are not planted individually, the geophone is mounted pendulously on a rotatable gimbal within an elongated streamlined housing, so that it will always be in its proper vertical position when resting on bottom. It is then customary to incorporate this special geophone housing as an integral part of the electrical cable so that the entire string comprising the geophone setup may be dragged on bottom from one location to the next. On the other hand, there are some water areas where ragged coral bottom precludes the use of this simple and time-saving method. In such cases, the geophones are lowered individually to the bottom. Some operations, especially over rugged bottoms, have been carried out by the use of suitable floats, whereby the geophones are actually suspended in the water, below the surface, where they partake in the seismic motion of the water just as they do when setting on bottom. Geophones actuated by the pressure waves in the water rather than the actual motional component of the seismic wave are particularly well adapted to the scheme of floating them below the surface. The writer is not informed as to whether pressure-type geophones have had any very extensive use, as there are certain embarrassing technical problems involved in their design.

Other than such innovations as the shot point and geophone spread and the obvious changes in operational procedure required to meet conditions of boat operation, there appear to be no novel departures from normal land operations that warrant detailed discussion here. In general, I believe it can be said that seismic operations in the Gulf of Mexico are very rapidly conducted and that, because of generally good bottom present over the area, the character of the records obtained surpasses that of the adjacent swamp lands.

V. THE DRILLING PHASE OF EXPLORATION

If, in the foregoing remarks, it appears that I have ignored drilling as a part of exploration procedure, let me hasten to add that I wish very strongly to emphasize its importance.

Regardless of the degree of perfection we might eventually attain in the resolving power of geophysical and geological tools with resultant achievement of near-perfect delineation of structural conditions, it is only the first step in exploration. The structure must, in the final phase, be tested by drilling, and must be proved to be a reservoir amenable to profitable exploitation. Thus production engineering and, in particular, drilling techniques are as essential to exploration as the geological and geophysical aspects of the problem of maintaining petroleum reserves. In many cases it represents the greatest portion of the cost. Of course, this is not a new concept, but I believe it is a phase of the problem which heretofore has been



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kept somewhat submerged by circumstances—circumstances whereby our search for new reserves was largely confined to provinces amenable to orthodox engineering and drilling techniques. Under such conditions the burden of finding new fields—or the failure to do so—fell almost entirely on the geologists and geophysicists, and discovery rates were determined largely by the success of their activities. Drilling for the purpose of condemning a location or of proving it was a more-or-less routine matter.

But now, in the industry's currently expanded operations, I wish to emphasize that in certain of these new provinces the crux of the problem will be, to a large extent, on the shoulders of the production engineer—not the geophysicists. This is particularly true of the continental shelf of Louisiana and Texas. Here is a vast area where long ago it was predicted that without doubt numerous salt-dome structures existed and, with almost equal certainty, that they would be productive. Moreover, no question was involved as to the ability of existing geophysical methods to locate such structures. Exploitation of the area has been entirely a matter of economics. Now, with the opening of the area, exploration is more or less a routine business, except for the introduction of certain innovations in operational techniques. Here for the first time, perhaps, the speed of development and, in fact, the areal extent of the exploitation will depend upon the ability of the industry to cope with the drilling and operational problems, and they will not be limited basically by the finding power of the geophysical tools.

Quite logically, at the present time, activity is confined to the combing of the near-shore waters for the larger features, viz., the geophysically obvious domes. Aside from certain special operational techniques, no unusual geophysical problems are involved; in fact, the finding of such domes is among the simplest of the geophysicist's problems. The number found will doubtless be in proportion to the distance out into the Gulf of Mexico that the production engineers are prepared to go. Moreover, current geophysical methods are quite capable of finding the less obvious deep-seated domes and even the relatively numerous, although somewhat obscure, interdomal features from which prolific production has been obtained on land. How many such features will enter the final exploration phase of drilling again will depend upon the economics of the exploration drilling problem. Thus it seems certain that the thoroughness with which this portion of our continental shelf is explored must ultimately be answered by the production engineers, not the geophysicists or geologists.

This is in some respects a unique situation; for, although deep-water exploitation is not a new accomplishment of the industry, the combination of problems in the Gulf is new, and drilling techniques and associated economics will for the first time be the major controlling factor in exploration—not the finding of reasonably promising drilling sites. This, I believe, is the most interesting and important feature of the Gulf of Mexico exploration activity. Certainly, I have no suggestions as to what form an exploratory drill might take that would provide the necessary economical follow-up on geophysical locations; perhaps there is no answer. But I do believe that the Gulf of Mexico exploitation will serve to highlight the need for bold attempts to replace the standard production rig for exploratory purposes. We should not forget the fact that the drill is as important a part of exploration as any of the geophysical tools, and it is deserving of as much effort in adapting it to this purpose.

* * *

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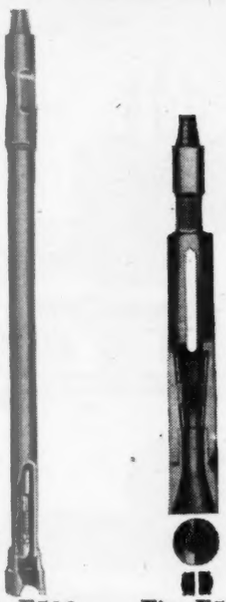

Fig. F533 Fig. F538

SPANG TUBING SPEAR
(Fig. F533)

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(Fig. F538)

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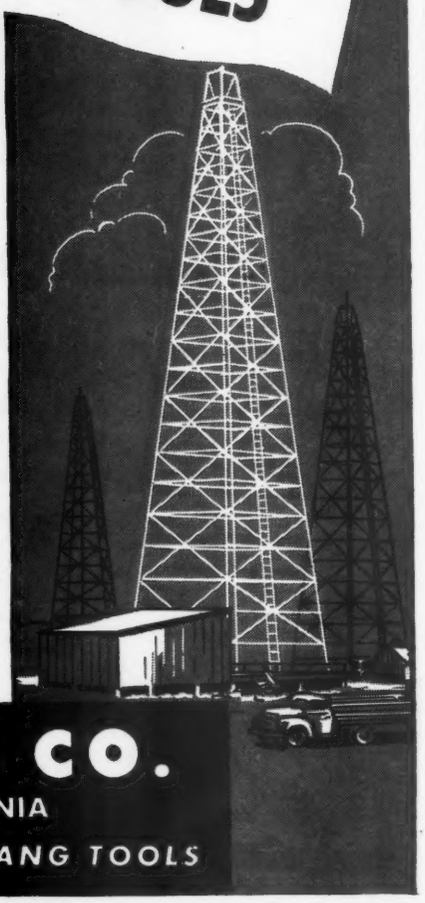

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FIRST, CONSIDER THE WORDS "COMBINATION BLOW-OUT PREVENTER AND STRIPPER": Unlike conventional pressure control equipment, this unit is BOTH a Blow-Out Preventer and a Stripper — combined into *one* compact unit. As a Blow-Out Preventer it maintains a *continuous* pressure-tight seal around *any* and *all* shapes and diameters* in the drill string — whether square, hexagon or octagon kellys... flush or upset pipe, couplings, tool joints or drill collars. That in itself is a very important advantage!

AND NOT ONLY DOES IT MAINTAIN THIS SEAL CONTINUOUSLY, but it also adjusts itself *instantly* and *automatically* to varying shapes and diameters as they pass through the unit — *all without manual attention of any kind.* Therefore it is a "Stripper" in the fullest sense of the word — a Stripper that *automatically* maintains complete pressure control even while the drill string is raised or lowered through the unit—*and no special pipe handling procedures are necessary.* So that's another very important advantage!

HOW ABOUT THAT WORD "ROTATING"? It highlights still another vital feature, for this unit is not only both a Blow-Out Preventer and a Stripper, but it also maintains complete pressure control *while the drill string is rotating.* It even maintains a leak-proof seal around *all* types of kellys while they rotate — even square ones — without damage or wear on the Stripper Rubber!

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In fact, although we have mentioned only a few of the many really unique features combined into the Shaffer Combination Rotating Blow-Out Preventer and Stripper, you can readily see that the name isn't half long enough. Before you invest in any pressure control equipment, why not let us give you the *complete* story on this versatile, trouble-free, highly-efficient Shaffer product?

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MUD CONTROL AND DESIGN

VICTOR HORNER AND W. B. KIMBRELL

Introduction

IN THE past few years, drilling fluids have become a major tool in the advancement of drilling technique and have opened an engineering field of vast importance to the oil industry. It has been recognized and well established that the inflow of gas or fluids and loss of drilling fluids are controllable by the correct application of hydrostatic principles and control of mud friction factors; that the transportation of cuttings is a matter of carrying power expressed through viscosity and gelation properties with consideration given to proper flow characteristics; that shale caving or sloughing is greatly influenced by the degree of water wetting of the shales; that the filtration cake deposited on the wall of the hole is related to mud quality and is a common source of trouble subject to correction; that the protection of permeability in reservoir zones is related to the chemical make-up of a mud and is a factor in initial production rate; that abrasive and corrosive actions of a mud are of sufficient importance to be concontrolled; that the value of electric loggings data is dependent upon the chemical character of a mud. These functions cover a broad field, some are interrelated, but as a whole, they are independent and each is sufficiently important and complex to justify specialized study.

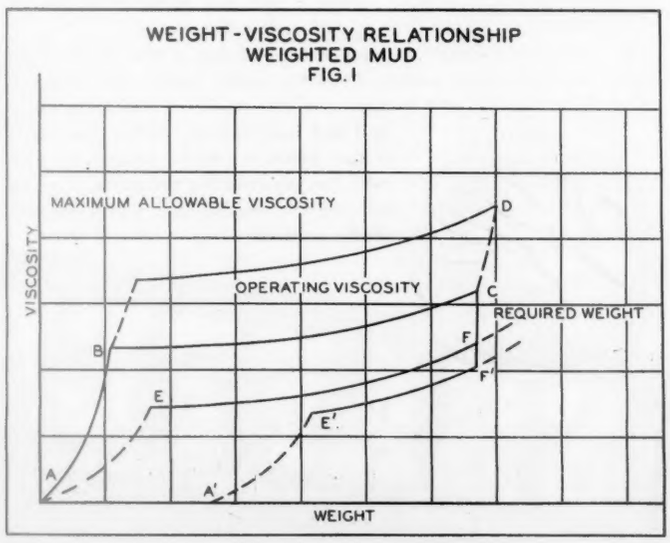
Weight Control

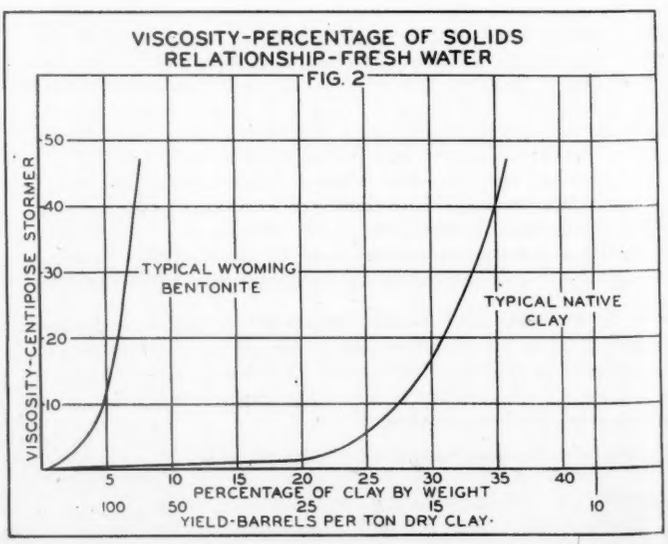
High specific gravity weight minerals (barite) have long been employed as an additive to drilling fluid for increasing mud density in the control of inflow of gas or fluids from the drilled formations. Mud weights in the 15 to 19 pounds per gallon range are in common use with today's deeper drilling, and present a complex problem in their design and control. Muds in this weight range must remain fluid with minimum viscosity to allow removal of entrained gas.

In preparing a weighted mud, barium sulphate, with a specific gravity of 4.3, is added to a prepared base mud, or to a base mud already in use in the drilling operation, and usually containing low specific gravity suspending material. As the weighting material is added for increased fluid density, the total effective volume percentage of solids increases. Dependent upon the effective per cent volume of low specific gravity material originally in the base mud, the amount of barite addition is, therefore, limited by resultant viscosity and gel strength. The same effect is realized when a weighted mud with satisfactory viscosity and gel strength properties is in use in drilling formations that add to the low specific gravity concentration; viscosity and gel strength increases would be expected.

Considering practical operating limits of viscosity and gelation, as weight requirement for a specific mud increases, or addition of low specific gravity solids occurs through drilling, the effective volume percentage of low specific gravity suspending material must be reduced. This may be done (1) by dilution and addition of barite; (2) by dehydrating the low specific gravity particles, or (3) by employing a higher specific gravity solution phase.

Figure 1 is a hypothetical representation of the viscosity-weight relationship of weighted muds showing the governing limitations and control approach. The line AB represents a hydrated or semi-hydrated clay added to fresh water as a suspending agent for the addition of barite along line B to C. The point C represents a mud designed for a required weight at operating viscosity. As low specific gravity solids are incorporated in the weighted mud along CD through drilling progress, the tendency of the mud is to slightly increase in weight and to increase in viscosity until the maximum allowable viscosity for release of entrained gas or fluid pumpability is reached at D. To control the viscosity below the maximum allowable, this mud may be diluted with fresh water to reduce the percentage of low specific solids with addition of barytes, if





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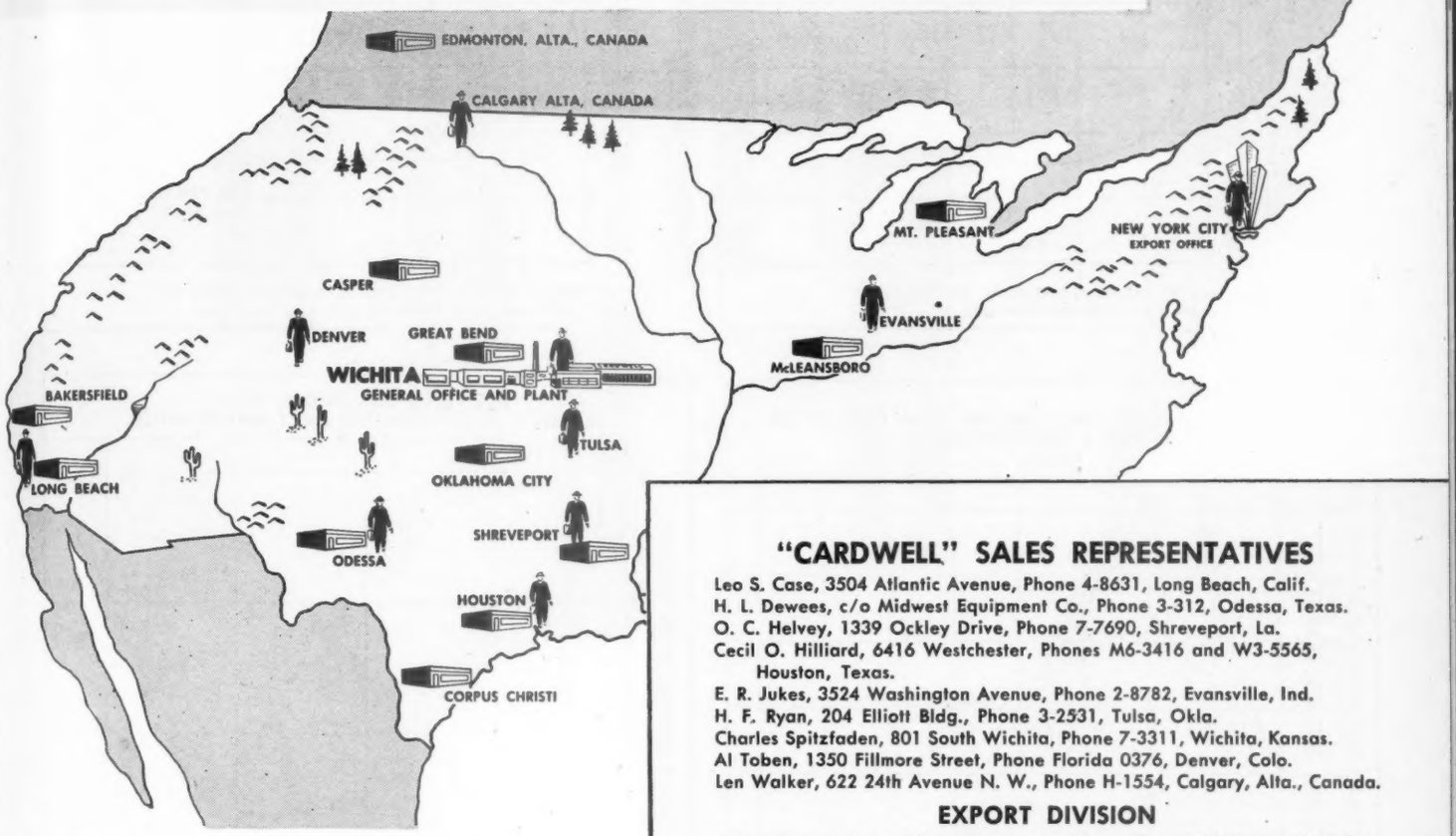

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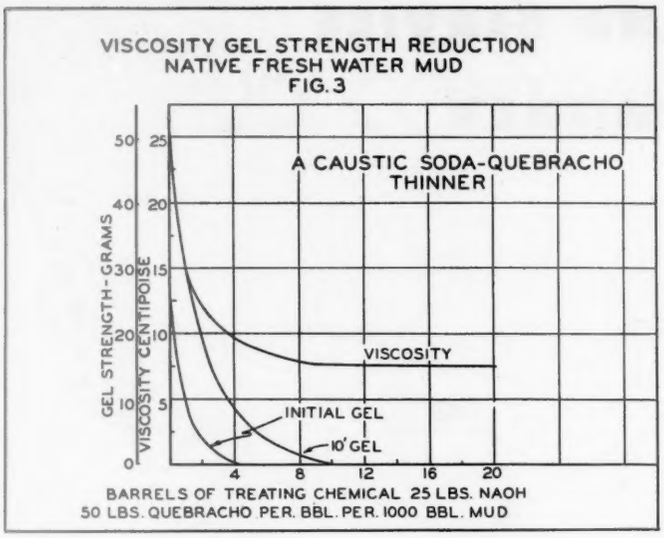
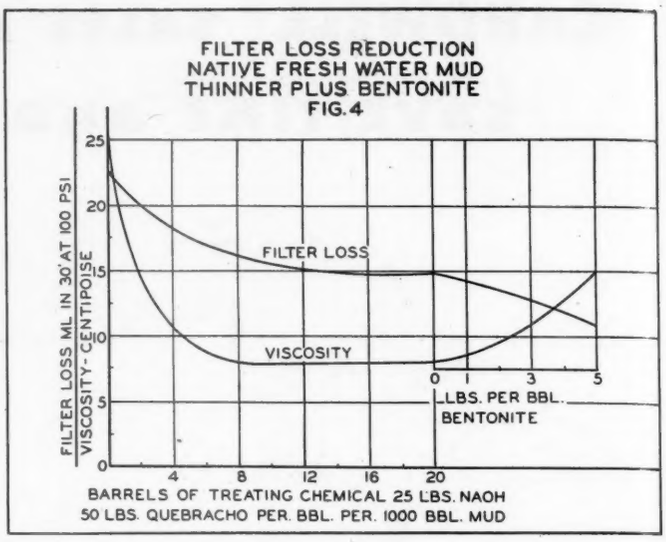
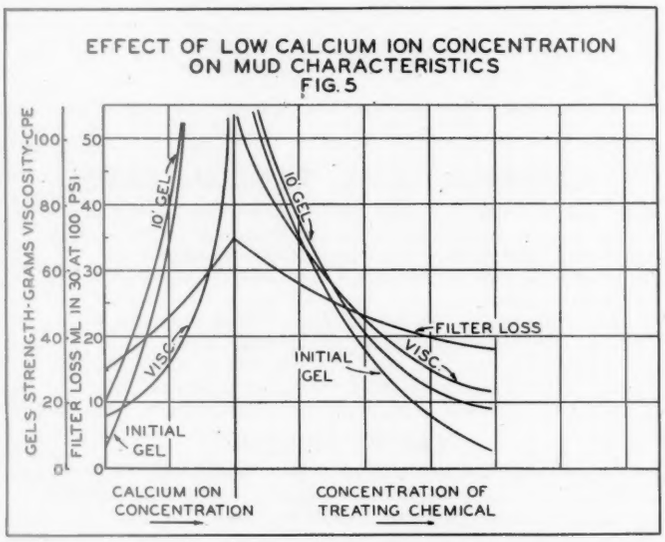
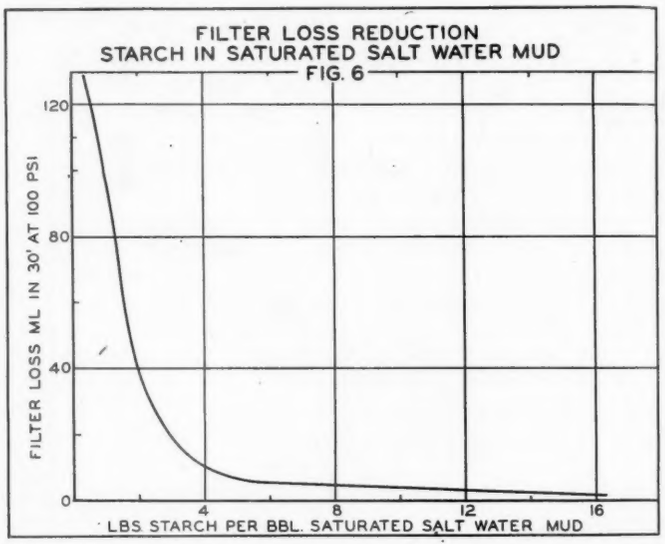



FILTER LOSS REDUCTION
NATIVE FRESH WATER MUD
THINNER PLUS BENTONITE
FIG. 4
FILTER LOSS ML IN 30' AT 100 PSI
VISCOSITY - CENTIPOISE
FILTER LOSS
VISCOSITY
LBS. PER BBL. BENTONITE
BARRELS OF TREATING CHEMICAL 25 LBS. NAOH
50 LBS. QUEBRACHO PER. BBL. PER. 1000 BBL. MUD




FILTER LOSS REDUCTION
STARCH IN SATURATED SALT WATER MUD
FIG. 6
FILTER LOSS ML IN 30' AT 100 PSI
LBS STARCH PER BBL. SATURATED SALT WATER MUD

necessary, to maintain the required weight. A second control method would be the chemical dehydration of the base clay AB or any hydrated clay added through drilling, CD, with the yield of these low specific gravity materials depressed to assume the position AE, which, together with the assistance of the high specific gravity weighting material along EF, would provide a reduced viscosity mud at the required weight at F. The third design or control method would be the use of a higher specific gravity liquid phase, such as saturated salt water. In this case the dehydrated base clay would assume the position of A'E' when mixed with the higher specific gravity liquid phase, and with the further addition of barytes along E'F' a mud would be provided with the required weight of a low viscosity.

Considering the limitation of viscosity, it may be noted that much higher weight muds may be prepared and controlled through the latter two design methods. The high weight muds in use today, vis., muds in the range of 15 to 19 lb per gallon, are mostly of these types.

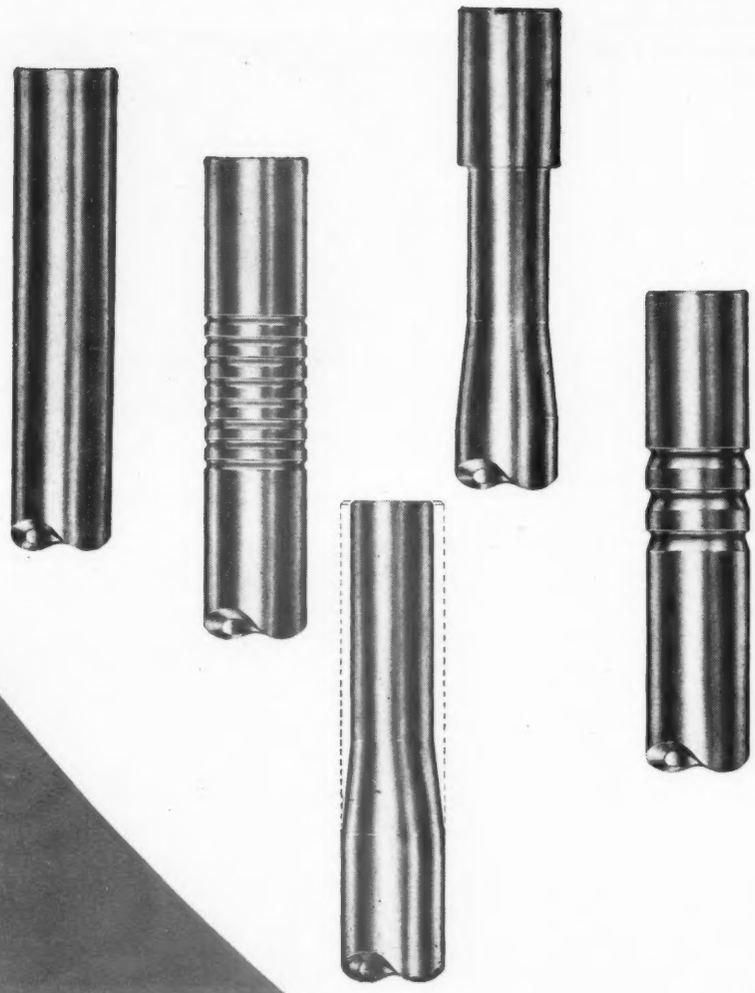
Control of highly weighted muds generally involves the matter of circulation loss where the mud weight must be controlled between the maximum permitted breakdown weight and the minimum required to overcome the formation pressures at hand. This condition generally places the weight at a fixed value with very little control tolerance. An understanding of the viscosity-weight relationship of weighted muds is particularly important in the design and control of such critical cases.

Viscosity and Gelation Control

Proper transportation of cuttings depends on the "carrying power" of the drilling mud to lift bit cuttings to the surface and yet allow the finer cuttings, not removed by the shale shaker, to settle in the surface pits. Viscosity and gelation control are related to the mechanical drilling operations where annular velocity, drilling rate, and mechanical hole erosion must be considered.

Because of its great ability to swell in water, bentonite has been the most widely used viscosity builder. Where viscosity is required in the design or control of a fresh water drilling mud, the high yield (expressed as the barrels of 15 centipoise mud per ton of clay) of Wyoming bentonite makes the material particularly adaptable for this purpose (Fig. 2). Other special clays have been developed and are in use for providing viscosity and gel strength in saline solutions.

Generally, improvement of flow characteristics through reduction of viscosity and gel strengths in fresh water-bentonite muds commands greater attention than increasing these values. Increases in viscosity and gel strengths due to hydration of clays from bit cuttings and hole erosion caused by drill pipe movement are common problems. Use of water, tanstuff and the polyphosphates to reduce viscosity and gel strength are control methods in common use. Fig. 3 show the action of a chemical thinner on a typical native fresh water bentonite mud.



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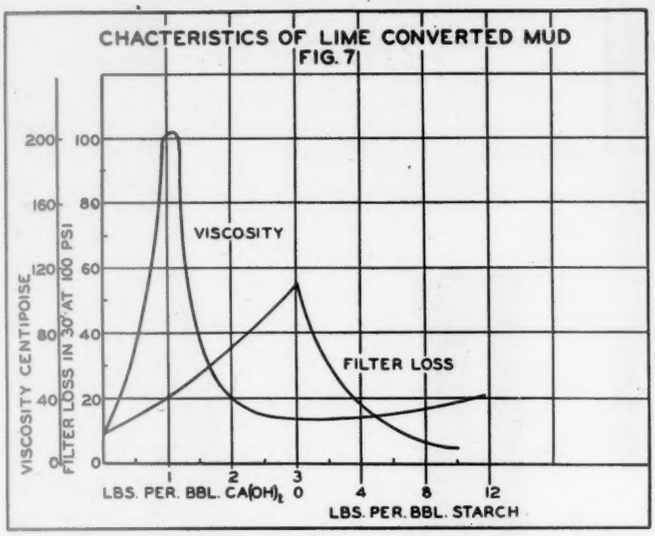


Control of Filtration Properties

The factor of water wettable shales involves control over the filtration properties, and development has depended upon the application of knowledge on colloidal suspensions. To minimize the filtration rate of a drilling mud requires consideration as to the type of colloidal material, colloidal particle size distribution, the degree of dispersion and the concentration of the colloid used. Common sources of colloidal particles are from clays, bentonites, starch, and other organic colloids.

One method of control involves the use of chemical mud thinners such as some of the tannin compounds and complex phosphates. They have been very effective in reducing the viscosity and gel strengths of muds to permit much higher concentration of colloidal particles for a given viscosity, and in controlling flow characteristics and filter loss in fresh water, bentonite type muds. Figure (4) illustrates the effect of concentrating colloidal particles through the thinning action of caustic soda-quebracho and addition of bentonite on water loss reduction of a fresh water native mud.

The colloidal particles supplied by bentonite and other clays are chemically active, and their behavior is influenced by chemical contamination; the multivalent cations have severest effect. The basis of chemical control of contaminants affecting viscosity, gel strength, and filter loss characteristics involves reactions where the multivalent cations are converted into an insoluble form and replaced by a single valent cation, generally sodium. This type treatment will minimize the flocculating forces and render the mud more fluid with a given concentration of colloidal particles. Fig. 5 depicts the effect of low calcium ion concentration on

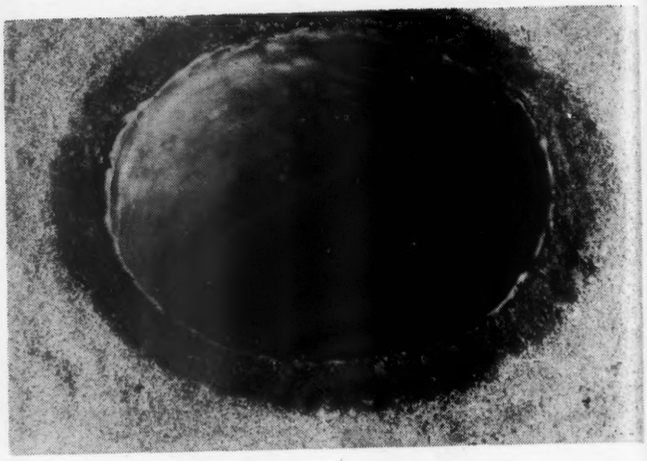


FIG. 8. Low filter loss wall cake.

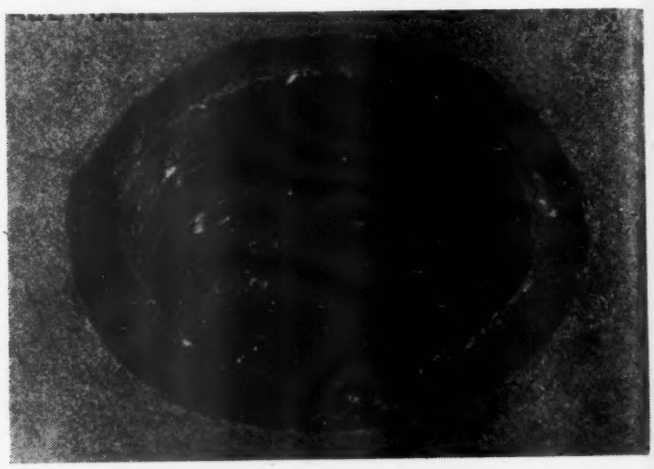
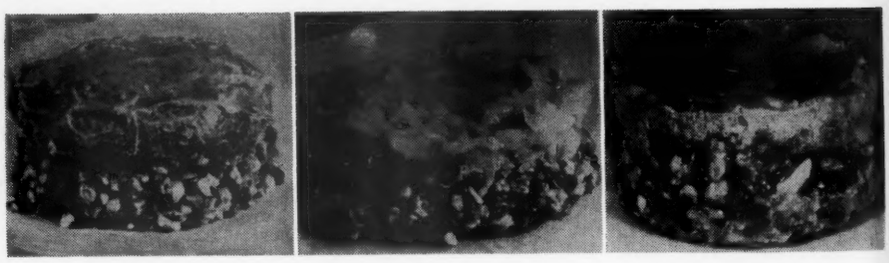


FIG. 8-A. High filter loss wall cake.

FIG. 9. Lost circulation materials.



a. Fibrous material. b. Cellophane foil. c. Mica.

FIG. 10. Mud balance.

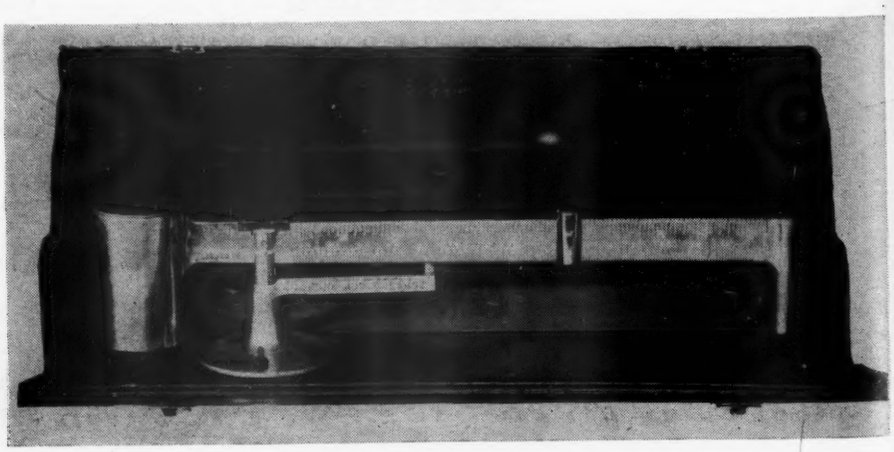


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FIG. 11. Marsh funnel viscosimeter.

mud characteristics and the restoration of desirable properties by removal of the calcium ion through precipitation. It is not the intent of these curves to cover the range of contaminate concentration and treatment, but rather to illustrate the effect of the presence of the multivalent cation calcium, in low concentrations, on mud properties. Control of such contamination can be effected by the use of sodium bicarbonate in the case of cement, by the use of sodium carbonate or barium carbonate for anhydrite. Regarding the latter, use of soda ash is limited by the concentration of sodium sulphate formed by the reaction, which can, in high concentrations, prove detrimental to most muds. Heavy anhydrite contamination is treated very effectively with barium carbonate, which removes calcium sulphate in its entirety.

More recently, attention has been given to special types of colloidal materials for control of mud filtration properties. It has been found that extremely low filter loss control depends upon maintaining a percentage of the colloidal material in the lower size range, and that a pliable type particle is desirable. The starch particle has been used effectively for this purpose and has afforded a means of producing extremely low filter rates. A sterile condition must be provided through use of bactericides, high salinity or high alkalinity. Starch is also extremely useful in that it is unaffected by high chemical concentrations. As a result, low filter loss muds can be produced under conditions of saturated salt (Fig. 6). The synthetic product, sodium carboxy-methyl cellulose, has similar characteristics and is finding application along the same line. In many applications this cellulose derivative has an even greater weight efficiency than commercially prepared starch in water loss reduction, and in addition presents very little fermentation hazard. These advantages are to some extent offset, however, by a higher price per unit weight.

Chemically dehydrating the clay particle in a conventional water-clay mud by the use of slacked lime alloys the preparation of a very stable mud having a wide application. In converting to a mud of this type, caustic soda and quebracho along with any necessary water dilution, is usually employed to assist in raising the alkalinity and to control viscosity and gel strength increases. The magnitude of viscosity increase during the dehydration process depends mainly on the concentration of hydrated clays in the original mud. Starch is used to reduce filter loss and the resulting mud is a very stable composition of starch and non-hydrated solids in a calcium saturated high pH solution. Such muds are particularly adaptable where high weights are required, are not affected adversely by chemical contamination, and through proper maintenance are very stable in regard to weight, viscosity and gel

FIG. 12. Stormer viscosimeter.

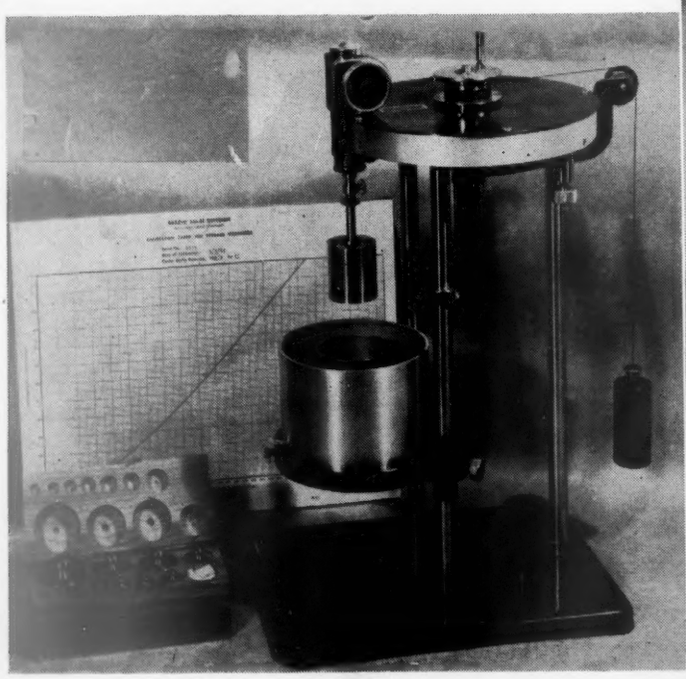
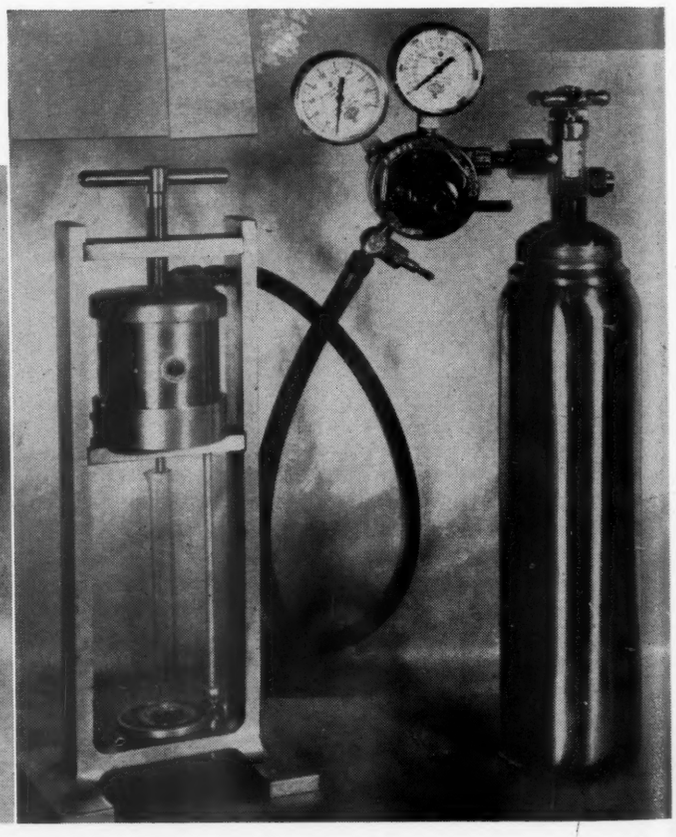


FIG. 13. Low pressure filter press.



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strength. Fig. 7 illustrates the change in mud characteristics for a lime converted mud.

A factor related to mud quality and filtration properties of a drilling fluid is the thickness of the filter cake deposited on the wall of the hole. This filter cake is usually proportional to the filter loss for a given mud. Figure 8 and 8A are visual representations comparing the effective diameter of a hole in sand in which a low filter loss mud has been circulated, and one in which high filter loss mud has been circulated. The high filter loss mud reduced the 8⅝-in. diameter to 6⅝-in. and illustrates the importance of minimizing cake thickness from the standpoint of sticking drill pipe and testing tools.

Where formation porosity and permeability are great enough to permit a partial or complete loss of drilling mud to the formation, bridging and plugging materials of a fibrous or flaky nature are incorporated in the mud. Fig. 9 illustrates the plugging action of mud ladened with several such materials.

Other Items of Control

Protection of permeability in reservoir zones may be related to the chemical composition of a mud and may be a factor in initial production rates. This thought had led to the use of extremely low filtrate fresh water muds, oil base muds and oil emulsion muds for well completion. Use of limed or salt water muds, or muds so treated that the filtrate would duplicate the chemical composition of formation interstitial water, are being tried.

Abrasive and corrosive action of drilling fluids are of sufficient importance to be controlled. Gel strength reduction through chemical treatment permits the dropping of abrasive sand cuttings in surface settling ditches and tanks. Sodium chromate and sodium nitrate are being used for retarding the corrosive effect of some drilling muds on drill pipe. A maintained concentration of 2000 ppm of either of these salts in the drilling mud has been found adequate to arrest any observable corrosion.

Interpretation of electric logging data is influenced by the effect of the chemicals in the mud upon the resistivity of the mud. It is most advantageous for sake of correlative interpretation of electric log data for mud resistivity to be within a suitable range.

Control Instruments

As the drilling mud engineer recognized the importance of drilling mud design and control to the complete operation, he developed instruments for measuring these properties to better prepare a basis for analytical study. The mud hydrometer or balance was devised for density measurements; the Marsh funnel and Stormer viscosimeter are used for viscosity and gel strength measurements; the Baroid low and high pressure filter press units were designed for evaluating filter loss and filter cake properties; a sand test kit was designed for measurement of amount of abrasive material; filtration analysis and alkalinity measurements are used for proper diagnosis and maintenance work (Figs. 11-13).

Conclusion

Mud test information from collected data at the well, including pilot testing, augmented with past experience, enable the chemical and petroleum engineer to design and control a drilling mud system for maximum operating efficiency. Collectively, the chemical and drilling engineer have contributed the greatest effort toward the development of present day drilling fluids, and are looked to for continued improvement towards the reduction of drilling hazards and costs.

* * *

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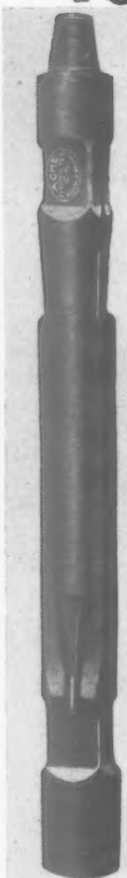

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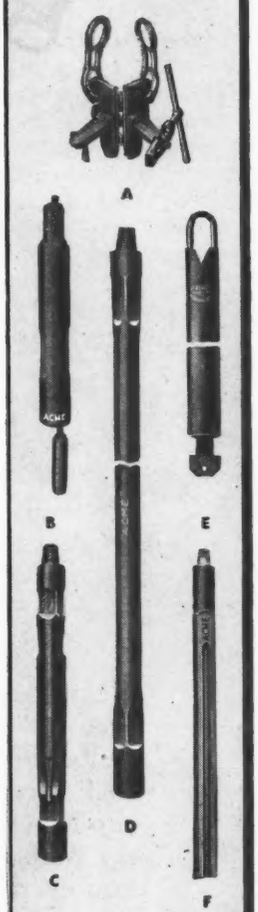

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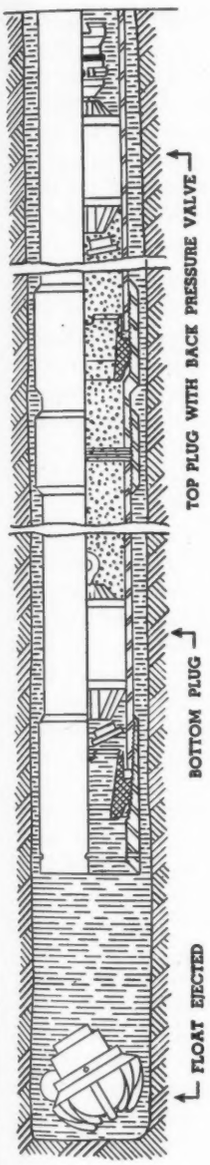
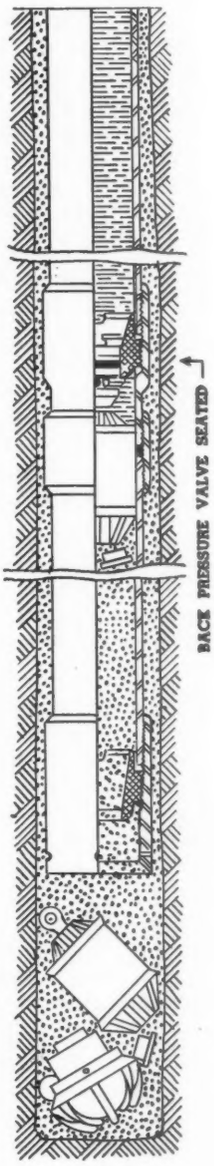
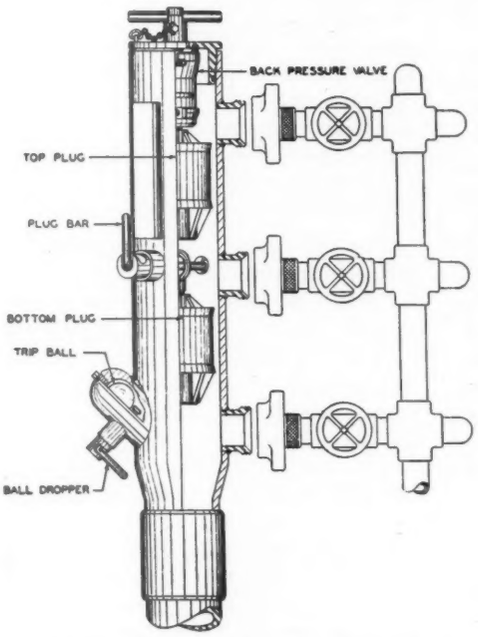


Job in progress Float assembly ejected from float shoe and bottom plug about to pass through float shoe.



Job completed. Top plug latched, and back pressure valve seated, in stall collar. Bottom plug ejected.



The model "E" cement head provides for dropping of trip ball and cementing plugs by simple external mechanical means, the minimum of shut down time. Head provides a closed circuit and shut in control at all times.

Numerous jobs have proved advancements which make these basic principles of the Rector "Fulbore" Cementing Method more effective than ever in obtaining efficient cement jobs:

1. **Full casing displacement for cement**
2. **Elimination of air in cementing flow circuit**
3. **Cement spaced from fluid by two plug method**
4. **Positive flow back control by piston type back pressure valve.**

FULL CASING DISPLACEMENT FOR CEMENT. The first of the two plugs used is dropped with the top of the mud column, clearing the casing of mud, segregating the mud and cement, and prevents slurry from becoming contaminated.

ELIMINATION OF AIR IN CEMENT FLOW CIRCUIT. The cement head is never opened from the time cementing operations begin until they are completed. It is impossible for air pockets to form in either mud or cement column. Trip ball and plugs are placed in the head before it is made up on the casing string.

CEMENT SEPARATED FROM FLUID BY TWO PLUGS. The first plug is released as soon as the correct volume of properly conditioned mud has been pumped in the well. When the proper amount of cement has been pumped in, the top plug with back pressure valve, is released and travels down with the cement until reaching and latching in the stall collar.

POSITIVE FLOW-BACK CONTROL. When the top plug with back pressure valve latches in the stall collar it prevents flow-back of cement. Operator may bleed the pressure back to zero and leave the well open, or close it in at final running pressure.

IMPROVED EQUIPMENT. The efficient operation of the "Fulbore" Method is assured by the improved cementing head, plugs, back pressure valve, float shoe and stall collar. For complete details of this cementing method and equipment, write for Bulletin No. 4-A,, "'Fulbore' Cementing Method and Equipment."

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Regulations Covering Drilling Activities in Coastal Waters†

R. G. WATTS*

Abstract

Because of the increasing number of wells being drilled in the coastal waters of the United States, especially in the Gulf of Mexico, it is most important that the companies who are conducting drilling operations in those areas become familiar with the regulations that govern these activities. In the ever-increasing tide of regulations, the oil industry is constantly becoming more involved. Heretofore on land operations we have been chiefly concerned with state and local regulations; but, when we move into navigable waters off our coast, we are immediately faced with new rules and governing agencies which in the past were alien to our operations. It is under these regulations that the oil industry must learn to operate in offshore and coastal drilling.

Permits

THE story has been told, in numerous professional papers and trade periodicals, of geophysical operation in the open waters of the Gulf of Mexico which results in the finding of geological structures conducive to the accumulation of oil; but, before an exploration crew can even leave the docks, there is first the matter of geophysical permits. These permits have proved of value not only to the state and federal government, but have been a protection to the operator as well.

The state of Louisiana requires three permits before exploration may be begun. In order to protect the marine life that abounds in gulf waters, the Department of Wild Life and Fisheries demands a permit for operating companies for the detonation of suspended charges up to 50 lb in the case of seismic surveying operations. Special dispensation is necessary for the use of larger charges, and the granting of this is left to the discretion of the department. It is necessary to show in the application, which must be made in triplicate, a map showing in detail the area that is to be explored. This permit is limited to four months, but can be renewed indefinitely upon subsequent request. It takes approximately 10 days to 2 weeks to obtain this permit, as well as each of the other necessary permits.

The second permit required by the state of Louisiana is that demanded by the State Mineral Board. This permit is good for a 6 months' period, but may be renewed for 2 additional 90-day periods by letter—a recent innovation as well as a convenient one. In the case of seismic work, if the exploration over the 700 square miles is incomplete at the end of this 12 months' period, the permit may be re-applied for on the conventional form. In the event the exploration is conducted over acreage already under lease to an operator other than the one conducting the survey, a certification of assent from the lessee must be included with the application. The state of Louisiana, as well as the U. S. Department of Army Engineers, also requires a police jury permit from the parish whose shore line is contiguous to the open water on which the survey is to take place.

The U. S. Coast Guard is likewise interested in marine operations; hence notice of the proposed survey must also be submitted to this agency. Boats used by the surveyor must conform to Coast Guard regulations and, further, any equipment or mechanism involving the use of explosives must conform to its specifications. Positions of buoys must be submitted to the Coast Guard at regular intervals.

When the described permits have been secured; and, when the state, the U. S. Engineers, and the Coast Guard have been notified of the proposed starting date, the exploration crew can begin its operations; but, before preparations for drilling can be started, there are several regulatory bodies that must be consulted. Some of these require permits before work is commenced.

First it is necessary to secure permission from the county or parish authorities to conduct operations within their boundaries or within the area over which they have jurisdiction, in the same manner as when geophysical work is proposed. Second, a permit from the state oil-and-gas regulatory body is required, the same as is required for land operations.

Third, inasmuch as operations are planned in navigable waters, we are obliged to come under the cognizance of the "laws for the protection and preservation of the navigable waters of the United States," known as the river-and-harbor act, which was passed by Congress, March 3, 1899. Sect. 10 of this act reads:

"That the creation of any obstruction not affirmatively authorized by Congress, to the navigable capacity of any of the waters of the United States, is hereby prohibited; and it shall not be lawful to build or commence the building of any wharf, pier, dolphin, boom, weir, break water, bulkhead, jetty, or other structures in any port, roadstead, haven, harbor, canal, navigable river, or other water of the United States, outside established harbor lines, or where no harbor lines have been established, except on plans recommended by the Chief of Engineers and authorized by the Secretary of War; and it shall not be lawful to excavate or fill, or in any manner to alter or modify the course, location, condition, or capacity of any port, roadstead, haven, harbor, canal, lake, harbor of refuge, or inclosure within the limits of any break water, or of the channel of any navigable water of the United States, unless the work has been recommended by the Chief of Engineers and authorized by the Secretary of War prior to beginning the same (30 Stat. 1151; 33 U. S. C. 403)."

This authorization is usually granted in the form of a permit. It is understood in all cases that this permit or instrument does not give any property rights, either in real estate or material, or any exclusive privileges; and that it does not authorize any in-

*Magnolia Petroleum Company, Dallas, Texas.

†Presented before annual meeting, American Petroleum Institute, Chicago, Illinois, November 8-11, 1948.

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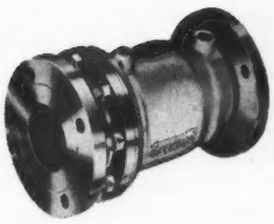

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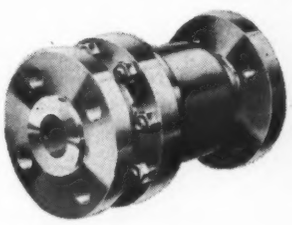

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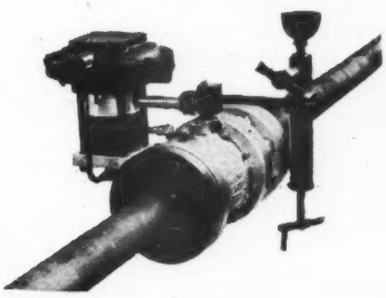

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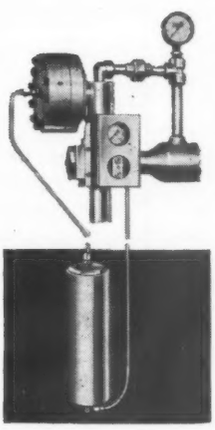

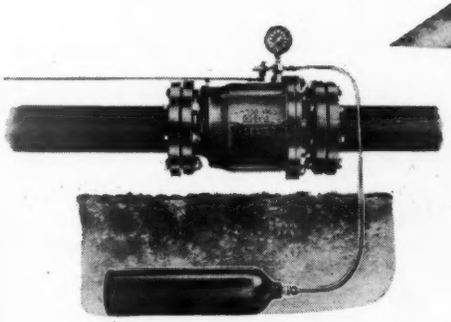

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jury to private property or invasion of private rights or any infringement of federal, state, or local laws or regulations. Also it does not obviate the necessity of obtaining state assent to the work that is authorized. The permit or instrument merely expresses the assent of the federal government in the concern of the public rights of navigation (see Cummings v. Chicago, 188 U. S. 410).

Instructions

Detailed instructions for mailing application to the U. S. War Department may be obtained from any district or division U. S. Engineer's office or the U. S. Government Printing Office in Washington, D. C. These instructions are entitled: "Information Circular: application for authority to execute work or erect structures in the navigable waters of the United States, 1939."

The application consists of a letter requesting the permit, accompanied by maps and plans of the proposed work. The letter of application may be addressed to the Secretary of War, but it will receive equal attention if it is addressed to the district engineer in charge of the locality in which the work is to take place. Such officers have general authority to issue permits for certain types of work, or they will forward to proper authorities the applications for permits on which they themselves cannot take final action. No printed application form is necessary. The letter of application, however, should bear the address of the applicant, together with the date, and contain the name of waterway, location, and description of the work, as well as a statement as to whether the work is within the corporate limits of a municipality. The description of the location must also include the name of the nearest well-known locality, preferably a city or town, and the distance and direction in miles and in tenths of miles from that location. The letter of application should give an explanation of the plans, so that the U. S. War Department officials may determine exactly what is proposed and can determine that the structure is not likely to fail or become a danger or obstruction to navigation or otherwise injure the navigable capacity of any public navigable waters. If dredging or dumping is proposed, the application should give the exact location of the work, the depth to which the proposed dredging is to be carried, the approximate amount of the material to be removed, and the definite location where the dredged material is to be dumped, as well as the depth of water that is to be left over it. Where dredging or dumping is proposed in connection with other work, a separate application for dredging is not required, but the information specified previously herein should be included in the application. Applications for dredging only may, if desired, be submitted by the dredging contractor who is to do the work.

To Aid British Oil Search

ECA has approved a British proposal whereby U. S. funds and techniques will be used to expedite a search for oil and other minerals in British colonial areas in Africa, Southeast Asia, and British Guiana. The U. S. Geological Survey is to recruit a party to serve with British Colonial Survey.

The district engineer is required to notify the municipal authorities of any application for proposed work that is within the corporate limits of a municipality. To save time and correspondence, every application for a permit should give the city or town within which the work is to take place, or it should definitely state that it lies outside of the limits of any city or incorporated town, unless such facts are clearly shown by maps and descriptions.

Letter of Application

The letter of application, and the attached papers and maps, should be complete, without reference to other correspondence not attached. It should include any special authorization for the work that is prerequisite to the action of the department, as, for example, a copy of the state permit for the work if the laws of the state in which the work is to take place require obtaining such instruments. The letter of application must also be signed by the owner or proprietor who proposes the work or by his duly authorized agent, and not by the contractor that is to be employed for the task—except in the case of applications for dredging permits. Letters of application should be made in triplicate, and signed copies and all attached papers should also be furnished in triplicate, whether the original or photostat copy. It usually requires about three weeks to obtain a permit after an application has been filed. These are issued under the following conditions:

a. That the work shall be subject to the supervision and approval of the district engineer, engineer department at large, in charge of the locality, who may temporaily suspend the work at any time if, in his judgment, the interests of navigation so require.

b. That any material dredged in the prosecution of the work therein authorized shall be removed evenly; and that no large refuse piles, ridges across the bed of the waterway, or deep holes that may have a tendency to cause injury to navigable channels or to the banks of the waterway shall be left. If any pipe, wire, or cable

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If pipe sticks, a collar is located in the blowout preventers, or rams freeze partly open, the preventers may be picked up in the conventional manner and the C-19 hanger wrapped around the pipe and seated in the head to give a permanent seal in a fraction of the time required by a conventional hanger.

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2. **Sealing element, slip bowl and slips are assembled as a single unit.**
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5. **The seal is automatic when casing weight is applied. No manual work required.**
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thereby authorized is laid in a trench, the formation of permanent ridges across the bed of the waterway shall be avoided, and the back-filling shall be done so as not to increase the cost of future dredging for navigation. Any material to be deposited or dumped under this authorization, either in the waterway or on shore above the high-water mark, shall be deposited or dumped at the locality shown on the drawing thereto attached; and, if so prescribed thereon, within or behind a good and substantial bulkhead or bulkheads such as will prevent escape of the material into the waterway.

c. That there shall be no unreasonable interference with navigation by the work therein authorized.

d. That, if inspections or any other operations by the United States are necessary in the interests of navigation, all expenses connected therewith shall be borne by the permittee.

e. That no attempt shall be made by the permittee or the owner to forbid the full and free use by the public of all navigable waters at or adjacent to the work or structure.

f. That, if future operations by the United States require an alteration in the position of the structure or work therein authorized, or if, in the opinion of the Secretary of War, it shall cause unreasonable obstruction to the free navigation of said water, the owner will be required, upon due notice from the Sercetary of War, to remove or alter the structural work or obstructions caused thereby without expense to the United States, so as to render navigation reasonably free, easy, and unobstructed; and if, upon expiration or revocation of this permit, the structure, fill excavation, or other modification of the water course thereby authorized shall not be completed, the owners shall, without expense to the United States, and to such extent and in such time and manner as the Secretary of War may require, remove all or any portion of the uncompleted structure or fill and restore to its former condition the navigable capacity of the water course. No claim shall be made against the United States on account of any such removal or alteration.

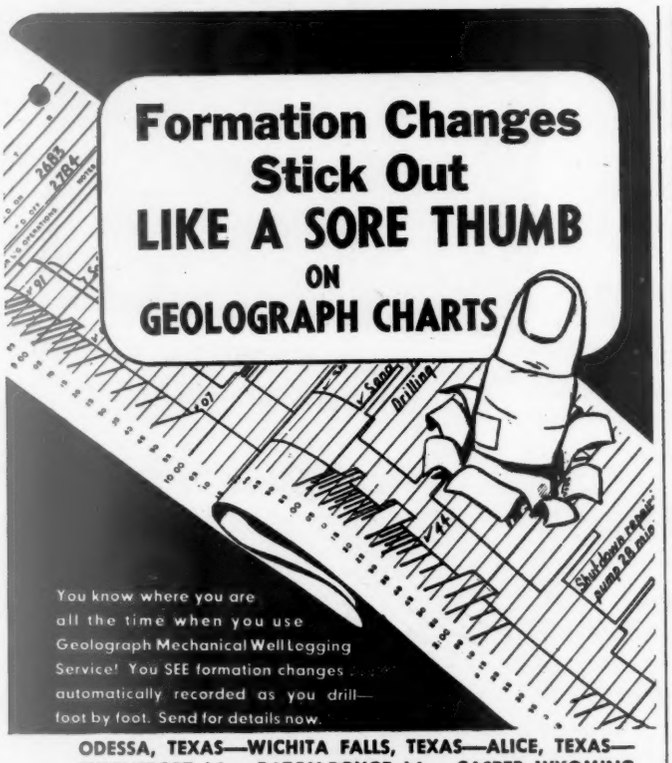
g. That the United States shall in no case be liable for any damage or injury to the structure or work therein authorized which may be caused by or result from future operations undertaken by the government for the conservation or improvement of navigation, or for other purposes; and no claim or right to compensation shall accrue for any such damage.

h. That, if the display of lights and signals on any work thereby authorized is not otherwise provided for by law, such lights and signals as may be prescribed by the U. S. Coast Guard shall be installed and maintained by and at the expense of the owner.

i. That the permittee shall notify the said district engineer at what time the work will be commenced, and as far in advance of the time of commencement as the said district engineer may specify; and shall also notify him promptly, in writing, of the commencement of work, suspension of work, i.e., if for a period of more than one week, resumption of work, and its completion.

j. That, if the structure or work therein authorized is not completed on or before a certain prescribed date, usually about three years, this permit, if not previously revoked or specifically extended, shall cease and be null and void.

k. That, in order to insure removal of the structures therein authorized at any time that they may become obstructive to navigation, or after they have ceased to be used for the purpose for which they are constructed, the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- Next, a series of heat-treating operations performed over the *entire length* of the Kelly in one operation, develop the metallurgical properties of the steel to provide the *best balance* of shock-resisting toughness and wear-resisting hardness.
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- The Kelly itself is also accurately surveyed for straightness and *must* be straight within one-*eighth* inch when measured at any point over its entire length.
- The alignment of the projected axis of each threaded end, when checked with the precise Baash-Ross Alignoscope, *must* be within one-*eighth* inch of the longitudinal axis of the Kelly for each 10 ft. of Kelly length, or fraction thereof.
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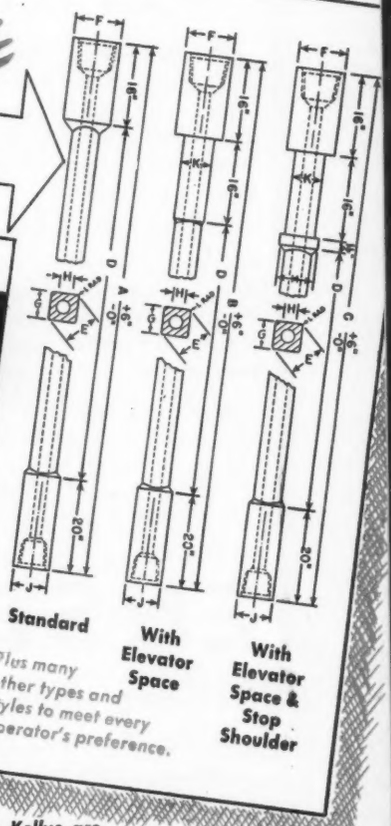
2½	35 38 40	36-4 39-4 41-4	36-6 39-6 41-6	32 35 37	4½ Reg. 6⅝ Reg.	5½* 7⅝	2⅝ Reg. 2⅝ I.F.	3¼ 3⅜	1¹⁄₁₆ 1¼	3⅜₁₆	2½	2¹³⁄₁₆	⅛	3⅝	*.165 .327
3	35 38 40	36-4 39-4 41-4	36-6 39-6 41-6	32 35 37	4½ Reg. 6⅝ Reg.	5½* 7⅝	2¾ Reg. 2⅞ I.F.	3⅝ 4⅛	1¼ 1⅜	3¹³⁄₁₆	3	2¹⁵⁄₁₆	⅜	4⅛	*.165 .327
3½	35 38 40	36-4 39-4 41-4	36-6 39-6 41-6	32 35 37	4½ Reg. 6⅝ Reg.	5½* 7⅝	3½ Reg. 3½ F.H. 3½ I.F.	4¼ 4⅝ 4⅞	1½ 2¼ 2¼	4¹³⁄₁₆	3½	3¹⁹⁄₃₂	½	4¾	*.165 .327
4½	35 38 40 84	36-4 39-4 41-4 55-4	36-6 39-6 41-6 55-6	32 35 37 51	4½ Reg. 6⅝ Reg.	5½* 7⅝	4½ Reg. 4½ F.H. 4½ I.F.	5¼* 5⅝ 6⅛	2¼ 2⅝ 2¾	5¹³⁄₁₆	4¼	4¹⁹⁄₃₂	½	5¾	*.165 .327
5½	38 40 84	39-4 41-4 55-4	39-6 41-6 55-6	35 37 51	6⅝ Reg.	7¾	5½ Reg. 5½ F.H. 5½ I.F.	6¾ 7 7⅜	2¾ 3⅛ 3¼	6²¹³⁄₃₂	5¼	5⅝	⅝	7	.327
6	38 40 84	39-4 41-4 55-4	39-6 41-6 55-6	35 37 51	6⅝ Reg.	7¾	6⅝ Reg. 6⅝ F.H.	7¾ 8	3½ 3½	7⅞	6	6¾	¾	8	.327

Sizes shown in BOLD are A.P.I. standard.
* Alternate 5¾ inches O.D.—.180 cu. ft. per lineal ft
† Volume based on largest diameter of kelly



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permittee is thereby required to furnish a bond in the sum of five thousand ($5,000.00) dollars, satisfactory to the Chief Engineers, before construction is commenced.

l. That, during both drilling and producing operations, the permittee shall take all necessary precautions—including, but not restricted to, installation, maintenance, and operation of blowout preventors, velocity chokes, and other tested devices; to preclude uncontrolled flow of oil through or around the casing or tubing or otherwise; and to prevent the well from becoming a menace to navigation or causing pollution of navigable waters.

m. That if, in the judgment of the Chief of Engineers, the said permittee does not at all times exercise due caution in the handling of oil to prevent conditions deleterious to health or sea food, or hazardous to navigation, or dangerous to persons or property engaged in commerce on said waters, this permit may be revoked and all operations authorized by it may be terminated.

The permit issued by the U. S. Department of Army Engineers only gives permission to install a structure or platform to be used in drilling operations, and does not contain all the regulations which govern transportation of equipment and other necessary items for the drilling of oil in coastal or offshore waters.

The U. S. Coast Guard has rules which require that any structure located in navigable waters must be marked by two 360-deg fixed or flashing red lights marking diagonally opposite corners. These lights should be visible at least one nautical mile on a dark night with a clear atmosphere. If flashing lights are used, the number of flashes should not exceed 30 per minute. If lights are to be exhibited from the drilling structure during drilling operations, it is not necessary to display the red obstruction lights until cessation of drilling operations. Any barges or boats used in conjunction with the fixed structure must maintain anchor lights as prescribed for a ship that is moored or at anchor.

If a protective structure is placed around the well upon removal of the drilling structure, this structure should be marked by one 360-deg red light located in such a manner as to be visible from any direction of the horizon. This light should be of the same type as described previously herein for drilling structures.

It is necessary to advise the U. S. Coast Guard when the lights are established, their description, any changes, and when they are discontinued, so that proper notice to mariners may be issued.

Coast Guard Jurisdiction

There have been volumes written concerning the laws and rules and regulations governing the building, operation, and manning of vessels used in the waters controlled by the United States. These laws and regulations are administered by the U. S. Coast Guard through its many district offices. They were adopted for the protection of life and property. The adoption of some of the laws dates back many years, and these laws were passed for conditions entirely different from those under which the oil prospectors and drillers are now working — causing undue hardship and expense to some of the companies. A committee has been formed, which is comprised of members representing many of the present companies drilling in the Gulf of Mexico, for the purpose of studying the existing laws and regulations, and for making suggestions for the revision of some of the laws which are now so burdensome. In making these suggested revisions, all care should be taken to maintain the provisions which guard the safety of personnel employed in this type of work. The U. S. Coast Guard is an organization which has proved very helpful in the solution of many problems which were strange to the oil companies in their early work on offshore drilling, and it should be consulted on all phases of work coming under its jurisdiction.

Height of Structures

In some localities, such as in the vicinity of airports or the army and navy practice areas, there are regulations governing the heights of any structures to be built. These areas can be determined by consulting local offices of the Civil Aeronautics Authority or the military authorities in those areas. As regards the Civil Aeronautics Authority, if a derrick or any other part of a structure extends more than 200 ft above the water, it is necessary to advise that authority, and to mark the top of the structure with a flashing red light.

FCC Jurisdiction

The Federal Communications Commission has promulgated rules and regulations covering the use of radio communication between shore installations and boats and wells at sea. There are two different types of equipment now in use, viz., frequency modulation, which is used for talking from ship to shore and to the well locations; and radio marine telephone, which is used for contacting the weather bureaus for weather forecasts and for direct communication by radio and telephone to any company's office. Permits must be secured from the Federal Communications Commission for the installation and operation of each of these systems. At the present time this governmental agency is making a survey for the purpose of assigning special wave lengths for the sole use of the oil companies in their offshore work.

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Performance of Hydraulic Type Rod Pumping Units in the Santa Fe Springs Field*

JUAN P. PEDRETTI†

Abstract

The performance of hydraulic type rod pumping units is discussed from the standpoint of the principal design features of the units and typical dynamometer cards are shown. Comparisons are made between the performance of the hydraulic units and that of the previously installed beam type units.

Introduction

PUMPING equipment for oil wells has in the past been largely designed around the combination of a crank and a walking beam. Early equipment was an adaptation of cable tool drilling equipment. Modern portable pumping units have evolved from the standard rig by the substitution of reducing gears for the belt and bandwheel, and the utilization of electric motors or high speed internal combustion engines as prime movers. The motion of the prime mover, however, is still converted into polished-rod stroke by means of cranks and a walking beam.

Throughout this development there has been a definite trend towards the use of longer stroke lengths. This trend has resulted not only from the desire for greater pump displacement but also from the desire to minimize rod, pump, and unit failures by utilizing slower speeds. Speeds between 17 and 25 strokes per minute, which were at one time commonly used in the oil fields, are now considered excessive by most production men. The increase in stroke lengths of beam-type pumping units from 12 in. on the early jacks to 12 ft on the larger modern pumping units has made it possible to lift larger volumes of oil and water, reduce peak loads, minimize sucker rod failures, and increase volumetric efficiency when producing gassy fluid.

In many California oil fields the water content of the production is increasing while fluid levels are declining, necessitating the pumping of larger volumes of liquid from greater depths in order to maintain economic rates of production. These factors make it advisable to resort to longer stroke lengths in order to minimize the troubles usually associated with large volume pumping. Since the use of a hydraulic system to transmit energy from the prime mover to the polished rod seems to offer a convenient method of obtaining almost unlimited stroke lengths, units embodying this principle have found a ready acceptance in certain areas. In the Santa Fe Springs field, for instance, there are approximately 45 hydraulic-type rod pumping units operating at stroke lengths from 10 to 26 ft. From the standpoint of operating performance it seems likely that stroke lengths in excess of 26 ft may prove feasible.

Although experience with hydraulic-type units has been relatively recent, it was felt that sufficient data could be obtained at this time to make possible significant comparisons between the performance of these units and that of the conventional beam-type equipment. In order to eliminate uncertainties resulting from the variations in behavior between wells, the wells studied were those in which beam-type units had been replaced by hydraulic. On this basis an attempt was made to compare maintenance and repair work on rods, tubing, pumps, and units under both methods of operation.

From the standpoint of this investigation it is unfortunate that the installations of hydraulic equipment were made largely to improve the operation of the wells and not primarily to obtain engineering data. For this reason other changes were often made at the same time that the surface equipment was changed. Since the hydraulic units were installed primarily to increase production from the wells, the plunger size or the pump depth or both were often increased, and in some cases, the rod string was redesigned or the tubing size changed. While these sources of uncertainty detract somewhat from the scientific precision of the analysis, it is felt that the general trends indicated by the data are significant, especially since the operating conditions were usually more severe subsequent to the installation of the hydraulic equipment.

TYPES OF HYDRAULIC UNITS

A hydraulic pumping unit consists of a piston which is connected to the polished rod and is operated by the force of a fluid under pressure inside a vertical cylinder. Some kind of pump and control valves are required to operate the piston so that it can be moved at will in either direction. Fluid which leaks past the piston and through the control valves is collected in a reservoir and returned to the system by a scavenging pump. In case the fluid is subjected to high pressures, a relief valve is provided to avoid damaging the hydraulic system. These items constitute the main components of the hydraulic system, but other auxiliary devices are sometimes used to improve performance.

Counterbalance

The well load transmitted to the hydraulic system by the polished-rod and piston is counterbalanced by an air-balance tank or by a counterweight. The purpose of a counterbalance is the same on a hydraulic as on a beam-type unit, that is, to minimize the variation in loading on the prime mover and transmission by storing energy on the downstroke and releasing it on the upstroke. In an air-balance type of system, the air in the tank is maintained at a predetermined pressure by a small air compressor. The excess fluid which develops through leakage past the piston or control valve drains back into the scavenger system, from which it is returned to the hydraulic system by a scavenger pump. The scavenger system can be closed or open, a closed system being one in which the fluid

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†Union Oil Company of California.

does not come in contact with the air during the process of recirculating to the hydraulic system.

Pump

The pump of the hydraulic unit is one of the most important parts of the hydraulic system. The three types of hydraulic units studied in this investigation can be classified by the type of pump used to circulate the power fluid: (1) A single suction, single stage centrifugal pump; (2) a triple-screw, positive displacement pump; and (3) a variable delivery piston displacement pump. These units will be designated as H1, H2, and H3, respectively. For the classification of units see Table 1 which follows:

TABLE 1. Classification of units.

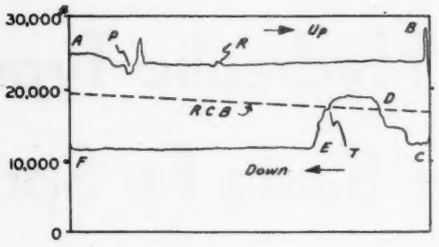
Type	Beam Type Unit: Allowable maximum torque (inch/pounds)	Allowable head load (pounds)	Stroke Length (inches)
B1a	260,000	29,600	66
B1b	375,000	29,600	86
B2a	137,000	19,500	54
B2b	137,000	20,000	54
B2c	137,000	25,000	72
B3	434,000	30,000	120

Type	Hydraulic Type Unit: Allowable head load (pounds)	Stroke Length (feet)
H1	25,000	26
H2a	25,000	20
H2b	35,000	20
H3	17,500	10

Reversing Valve

The reversing mechanism on a hydraulic unit usually consists of a small pilot valve, actuated by either hydraulic or mechanical means, which operates the main reversing valve. The H1 unit has both types of reversing mechanisms—at the bottom of the downstroke, the unit is reversed mechanically as the piston inside the cylinder trips a lever, which in turn displaces the pilot valve. At the top of the upstroke the pilot valve is actuated by the differential pressure between the top and bottom of the piston. The reversing mechanisms of the H2 unit are both hydraulically actuated. The pilot valve of the reversing valve is actuated by the differential pressure between the air-balance and the cylinder, being actuated by the pressure above the piston at the top of the upstroke and by the pressure below the piston at the bottom of the downstroke. The reversing mechanism of the H3 unit is mechanically actuated at both ends of the stroke by the movement of the piston in the counterbalance cylinder.

FIG. 1



P—Pump Pickup
T—Traveling Valve open
R—Reflection
C.B.—Counterbalance

Field: Santa Fe Springs
Well: W
Date Tested: 9-28-48
Zone: O'Connell

Rods: ¾": 2820
⅞": 2520
1": 960
Tubing: 2½"-7052
Pump Size: 2½x2x35
Pump Depth: 7022'

Pumping Unit: H1
Cyl. Pressure: 125-300 psi
Air Bal. Pres.: 205-235 psi
Polished Rod: 1½"
Stroke Length: 26.6'
Speed: 500 SPM

Production:
Gross: 417 B/D
Net: 195 B/D
Cut: 55.2%
Gravity: 33.7°API

Mx. Cyl. Load: 27,500#
Min. Cyl. Load: 11,200#
Cylinder H. P.: 41.4
Actual C.B.: 17,320#
Require C.B.: 17,180#

INFLUENCE OF DESIGN ON PERFORMANCE

Pump

Although it is not within the scope of this paper to discuss the details of the design of hydraulic units, something should be said about the influence of the design upon the actual performance of the unit. Possibly the most important feature of the design is the selection of the pump for the hydraulic system, since the characteristics of the pump directly affect the variation of polished-rod load and speed. For instance, a centrifugal pump, because of the slippage inherent in its design, will tend to maintain a constant load on the polished rod but will permit a variation in velocity during the stroke. A positive displacement pump, on the other hand, will tend to maintain a constant polished-rod velocity but will permit a variation in load as a result of disturbances originating in the well. Other things being equal, a centrifugal pump might be expected to minimize rod trouble, while a positive displacement pump might be expected to result in a higher mechanical efficiency for the unit and possibly higher volumetric efficiency for the subsurface pump.

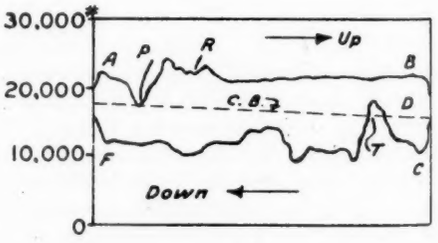
Hydraulic Fluid

Another basic design factor is the selection of the hydraulic fluid. In some hydraulic units the fluid is water in which is emulsified a small amount of "soluble oil" while in others the fluid is a light refined oil such as turbine oil. The higher density and lower viscosity of water seem likely to result in higher mechanical efficiency, while the relatively higher viscosity of oil seems likely to minimize shock loading caused by the water-hammer effect. Obviously, the hydraulic fluid must be as stable as possible when exposed to variations in temperature and to oxidizing conditions.

Counterbalance

The counterbalance design has a definite influence upon the performance of the hydraulic unit. In the air-balance type, the effective counterbalance varies from a maximum at the bottom of the stroke to a minimum

FIG. 2



P—Pump Pickup
T—Traveling Valve open
R—Reflection
C.B.—Counterbalance

Field: Santa Fe Springs
Well: Q
Date Tested: 10-8-48
Zone: O'Connell

Rods: ¾": 2880
⅞": 1440
1": 2280
Tubing: 2½"—6786'
Pump Size: 2½"x2x30
Pump Depth: 6760'

Pumping Unit: H2a
Cyl. Pressure: 275-475 psi
Air Bal. Pres.: 350-400 psi
Polished Rod: 1½"
Stroke Length: 18.3'
Speed: 7.06 SPM

Production:
Gross: 488 B/D
Net: 336 B/D
Cut: 31.2%
Gravity: 33.7 API

Mx. Cyl. Load: 24,600#
Min. Cyl. Load: 9,220#
Cylinder H. P.: 35.0
Actual C.B.—16,800#
Require C.B.—16,725#

TABLE 2. Characteristics of hydraulic units.

Type unit	Type pump	Power fluid	Type counterbalance	Type scavenger system	Type of reversing mechanism: Top stroke	Bottom stroke
H1	Centrifugal	Water with "soluble oil"	Air	Open	Hydraulic	Mechanical
H2	Displacement	Oil	Air	Closed	Hydraulic	Hydraulic
H3	Displacement	Oil	Weight	Open	Mechanical	Mechanical

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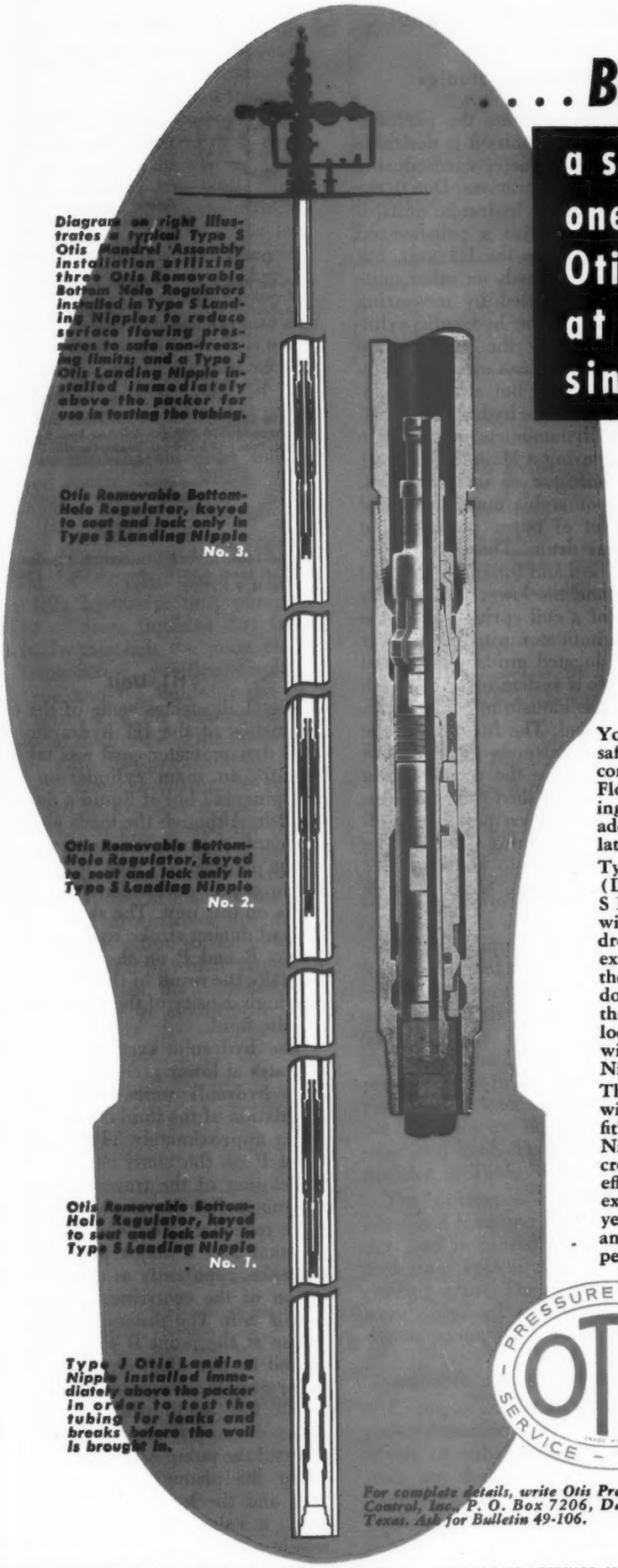
Diagram on right illustrates a typical Type S Otis Mandrel Assembly installation utilizing three Otis Removable Bottom Hole Regulators installed in Type S Landing Nipples to reduce surface flowing pressures to safe non-freezing limits; and a Type J Otis Landing Nipple installed immediately above the packer for use in testing the tubing.
Otis Removable Bottom-Hole Regulator, keyed to seat and lock only in Type S Landing Nipple No. 3.
Otis Removable Bottom-Hole Regulator, keyed to seat and lock only in Type S Landing Nipple No. 2.
Otis Removable Bottom-Hole Regulator, keyed to seat and lock only in Type S Landing Nipple No. 1.
Type J Otis Landing Nipple installed immediately above the packer in order to test the tubing for leaks and breaks before the well is brought in.

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Your next high-pressure well can have simpler and still safer sub-surface control. One, two, three, or more new corrosion-resistant Type S Otis Landing Nipples (and Flow Couplings), run at desired intervals with the tubing, will afford definitely located seats for landing an adequate number of Otis Removable Bottom Hole Regulators, Tubing Safety Valves, and Bottom Hole Chokes.

Type S Otis Landing Nipples are essentially full-opening. (Drift diameter of 2" tubing = 1.901"; I. D. of 2" Type S Landing Nipple = 1.875".) Each Nipple is "profiled" within its bore to accept only one specific Type S Mandrel Assembly having a matching set of "keys." For example, the Type S Mandrel with #1 keys, and carrying the desired sub-surface control mechanism, can be run down the tubing under pressure on a steel measuring line through all upper Type S Landing Nipples, to select and lock positively only in Type S Landing Nipple #1. Likewise, the Assembly having #2 keys can be set only in Nipple #2, etc.

The new Type S Otis Mandrel Assemblies are equipped with fully-supported V-type packing which effect a "slide fit" within the machined bore of the Type S Landing Nipple to eliminate the necessity of flowing the well to create an initial shutoff, and are constructed with an efficient metal-to-metal locking mechanism. These two exclusive design features have been used successfully for years (in Type J Otis Mandrel Assemblies) to pack-off and lock Otis Sub-Surface Controls under extreme temperature and pressure conditions.

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TYPE S MANDREL ASSEMBLY

(T-25)

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at the top of the stroke. The greater the variation of the pressure in the air-balance cylinder, the greater the variation of the rate at which hydraulic fluid is pumped, as the pressure differential between the well cylinder and the air-balance varies accordingly. Where the air-balance pressure is used to operate the pilot valve of the reversing mechanism, a relatively large variation in air pressure, together with a large variation in polished-rod load, may result in premature reversals. It has been observed in the field that, as the temperature changes during the day, the effective air counterbalance also changes slightly. Obviously the counterweight type of counterbalance eliminates these variations.

In the case of the H1 and H2 hydraulic units, as the power fluid comes in contact with the compressed air in the air-balance tank, some air is absorbed by the power fluid and it becomes in consequence slightly corrosive and compressible. This condition is avoided in the H3 unit by the use of a counterweight operated by a cylinder similar to the well cylinder. Since the hydraulic fluid is transmitted between the cylinders in a closed system, the fluid is never in contact with air at high pressures.

Summary

The principal features of the hydraulic pumping units studied in the Santa Fe Springs field are summarized in Table 2.

PERFORMANCE OF HYDRAULIC UNITS

Dynamometer Studies

In order to evaluate the performance of hydraulic units it is desirable to obtain dynamometer cards during actual pumping operations. Due to the construction of the hydraulic units, it is possible to utilize a polished-rod dynagraph only on the H3 unit, but the polished rod loads on other units can be approximated by measuring the pressures in the hydraulic cylinder. Unfortunately the pressures in the cylinder reflect not only the variations in well load, but also the pressure variation in the hydraulic circuit. Most of the dynamometer charts were obtained by using a Maihak (Crosby) standard indicator or its equivalent. The pencil or stylus makes a record upon a sheet of paper placed about the indicator drum. The drum is rotated backward and forward by a cord wound around the lower part and by the action of a coil spring within the drum. The indicator cord is run over a properly located guide pulley, and is attached to a system of wheels with a reducing mechanism in contact with the polished rod. The function of the reducing mechanism is to reproduce on a smaller scale the reciprocating motion of the polished-rod. Unfortunately it has not been possible to attach an adequate timing device to the instrument in order to allow a more thorough study of the characteristics of the system.

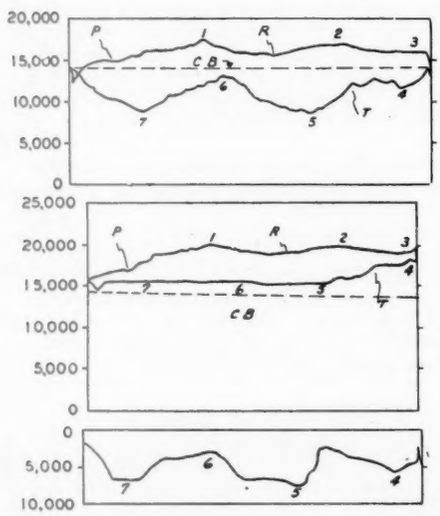


FIG. 3a

FIG. 3b

FIG. 3c

P—Pump Pickup
T—Traveling Valve open
R—Reflection
C.B.—Counterbalance

Field: Santa Fe Springs
Well: T
Date Tested: 3-3-49
Zone: Clark

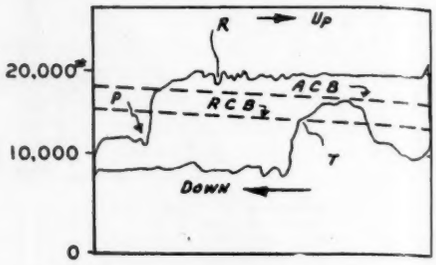
Rods: ¾": 4980'
⅞": 2160'
Tubing: 2"—7238
Pump Size: 2x1½x20'
Pump Depth: 7192

Pumping Unit: H3
Cyl. Pres.: 1800-1340 psi
Air Bal. Pres.: 1300 psi
Polished Rod: 1¼"
Stroke Length: 10'6"
Speed: 6.25 SPM

Production:
Gross: 97 B/D
Net: 30 B/D
Cut: 68.9%
Gravity: 32.5° API

Mx. Cyl. Load: 1820
Min. Cyl. Load: 770
Actual C.B.: 14,000#
Mx. Pol. Rod Load: 17,400
Min. Pol. Rod Load: 8,470
Polished Rod H. P.: 9.97

FIG. 4



P—Pump Pickup
T—Traveling Valve open
R—Reflection
Field: Santa Fe Springs
ACB—Actual Counterbalance
RCB—Required Counterbalance

Well: H
Date Tested: 11-9-48

Rods: ¾"—2820'
⅞"—1980'
1"— 990'
Zone: Buckbee
Tubing: 2½—5864'
Pump Size: 2½x2¼x30

Pumping Unit: H1
Cyl. Pressure: 100-300 psi
Air Bal. Pres.: 195-218 psi
Pump Depth: 5838
Polished Rod: 1½"
Stroke Length: 21'
Speed: 5.32 SPM

Production:
Gross: 341 B/D
Net: 48 B/D
Cut: 85.9%
Gravity: 33.8° API

Mx. Cyl. Load: 20,700#
Min. Cyl. Load: 6,850#
Cylinder H. P.: 19.05
Actual CB: 16,600#
Require CB: 13,785#

H1 Unit

Fig. 1 illustrates some of the characteristics of the H1 hydraulic unit. This dynamometer card was taken on the 10¼-in. diam. cylinder on a well pumping 417 bbl of liquid a day from 7022 ft. Although the loads shown on the card are only an approximation of the polished-rod load, it is impossible to obtain polished-rod dynagraph cards on this unit. The sharp changes in load during stroke reversals and at points B and P on the card may be partially the result of the low viscosity and high density of the water base hydraulic fluid.

The hydraulic system in the unit operates at lower pressure than in the other hydraulic units, but the rate of circulation of the fluid is higher, averaging approximately 1100 gpm. The point P on the chart corresponds to the closing of the travelling valve of the sub-surface pump and R to its full wave reflection. The load is relatively constant over a major portion of the upstroke, apparently as a result of the action of the centrifugal pump used in this unit. The pronounced load increase at the point B of the chart is caused by the effect on the hydraulic reversing mechanism on the fluid which has accumulated above the piston due to leakage. After the stroke reversal the pump displaces fluid from under the piston to the air-balance tank and the load decreases from B to C, a value slightly less than the weight of the rods. It cannot be determined just which portion of the load range BC results from the action of the hydraulic system and which por-

tion actually corresponds to the change in polished-rod load. From C to D, the well load tends to compress the fluid in the cylinder, and the pressure in the cylinder increases to a value almost equivalent to the weight of rods and liquid in the well. At T the travelling valve of the well pump opens and the pressure in the cylinder decreases from T to E, a value less than the weight of the rods. The constant load from E to F on the chart is probably due again to the action of the centrifugal pump. The time interval in the chart from B to T is very small with respect to the rest of the downstroke. The little step in the downstroke between C and D is probably a reflection. The hump AP on the chart is probably caused by inertia of the rod system.

H2 Unit

The chart represented by Fig. 2 was obtained on the 8-in. diam. cylinder of an H2a hydraulic unit pumping 448 bbl of gross liquid a day from 6760 ft. In this unit the main pump is a triple-screw, positive displacement type and the fluid for the hydraulic circuit is oil. Because of the viscosity of the fluid and the lower circulation rate (approximately 650 gpm) load changes during the reversals of stroke are less sudden than those shown in Fig. 1, and the loads shown on the chart probably approximate the polished-rod load more closely. The variations in load during the upstroke and downstroke are probably due to the action of the positive displacement pump which tends to deliver a constant fluid volume regardless of pressure conditions.

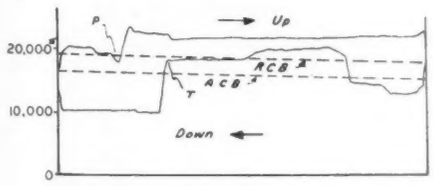


FIG. 5

P—Pump Pickup
T—Traveling Valve open
R—Reflection
Field: Santa Fe Springs
Well: H
Rods: ¾"—2820'
⅞"—1980'
1"— 990'
Pumping Unit: H1
Cyl. Pressure: 130-290 psi
Air Bal. Pres.: 178-200 psi
ACB—Actual Counterbalance
RCB—Required Counterbalance
Date Tested: 1-10-49
Zone: Buckbee
Tubing: 2½"—5864'
Pump Size: 2½x2¼x30'
Pump Depth: 5838'
Polished Rod: 1½"
Stroke Length: 22.9'
Speed: 4.73 SPM

Production:
Gross: 199 B/D
Net: 28 B/D
Cut: 85.9%
Gravity: 33.8°API

Mx. Cyl. Load: 23,000#
Min. Cyl. Load: 9,430#
Cylinder H. P.: 19.8
Actual CB: 15,200#
Require CB: 17,840#

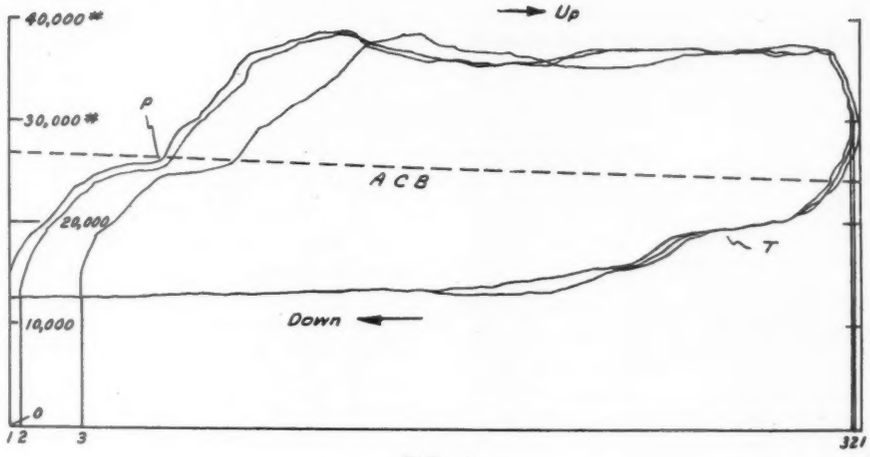


FIG. 6

P—Pump Pickup
T—Traveling Valve open
Field: Santa Fe Springs
Well: Z
Rods: ⅞"—5070'
Rods 1"—1950'
Pumping Unit: H_2b
Cylinder Pressure: 205-565 psi
Air Balance Pressure: 385-428 psi
R—Reflection
ACB—Actual Counterbalance
Date Tested: 12-23-48
Zone: Clark
Tubing: 2½"—7147'
Pump Size: 2½x2x32
Pump Depth: 7116'
Polished Rod: 1¾"
Speed (aver.): 6.41 SPM
Stroke Length: 1) 14.67'
2) 14.32'
3) 13.20'

Production:
Gross: 214 B/D
Net: 2 B/D
Cut: 99.0%
Gravity: 33.1° API

Mx. Cylinder Load: 37,800#
Min. Cylinder Load: 12,250#
Cylinder H. P. (aver.): 47.5
Actual C. B.: 25,300#
Required C. B. (aver.): 24,140#

H3 Unit

The dynagraph represented by Fig. 3 was obtained (a) on the polished rod; (b) on the bottom part of the 4-in. diam. well cylinder, and (c) on the line connected to the top of the 4-in. diam. well cylinder on an H3 type unit. The well was producing 97 bbl of gross liquid per day from 7192 ft. The pump of the hydraulic unit circulated an average of 86 gal of oil per minute at a high pressure in the system (average 1650 psi). It seems likely that the low volume and high pressure used in this hydraulic system results in a closer correlation between net pressure on the piston and polished-rod load. This relation is summarized in Table 3.

The difference between the polished-rod load and the effective cylinder load is caused by friction in the hydraulic system and instrument recording error. The polished-rod loads were obtained with a Westinghouse dynamometer instrument.

Diagnosis of Subsurface Trouble

Examples of the application of cylinder dynamometer cards to the analysis of subsurface pump performance are shown in Fig. 4, 5, and 6. Analysis of the chart shown in Fig. 4 indicated that the pump plunger was hitting down, an interpretation which was subsequently verified by the production crew. In Fig. 5, for the same hydraulic unit, fluid pound was caused by restriction of the pump intake due to the formation of scale. During the period previous to a pump change, a fluid level determination indicated a fluid level considerably above the pump. Fig. 6 illustrates excessive maximum loading and load range caused by the plunger sticking in the pump. The great difference between maximum and minimum loads also resulted in premature reversal of the stroke since the pilot valve is hydraulically controlled in this unit.

Hydraulic Fluid

To insure proper functioning of the oil used as the hydraulic fluid in some units it is desirable to make periodic tests for viscosity, gravity, acid number, bottom sediment and water, and iron content. After making semi-monthly tests for 40 months it was found that such properties of the oil as gravity and viscosity did not change

TABLE 3. Hydraulic unit Type H3—dynagraph cards comparison.

Card* position	Lb polished-rod load	Well cylinder load: Lb below piston	Well cylinder load: Lb above piston	Well cylinder load: Lb effective cylinder load
P	15,080	16,880	1,635	15,245
1	17,400	20,200	1,635	18,565
R	15,520	19,000	1,635	17,365
2	16,850	19,870	1,635	18,235
3	15,800	19,200	1,635	17,565
4	11,550	17,870	5,660	12,210
5	8,470	15,540	7,920	7,620
6	12,870	15,820	2,764	13,056
7	8,920	15,750	6,660	9,090

*See fig. 3 for relative position on the charts.

TABLE 4. Hydraulic oil consumption data.
(Based on period from Jan. 1, 1947 to Dec. 9, 1948)

Pumping unit	Type of oil	Number of units	Average Consumption (gal/day)
H1	Soluble	3	0.26
H2	Turbine	19	2.35
H3	Turbine	8	1.00

significantly, but B. S. and W., acid number, and iron content showed some tendency to increase with service. Impurities in the oil such as water and air apparently cause oxidation of the oil and corrosion of the metals in the unit. In order to maintain satisfactory operation of the units, it was necessary to add a filter screen in several H2 units to remove foreign matter from the oil. By this means the sediment and iron content of the oil was greatly reduced and the acid number was somewhat improved. Hydraulic fluid for the H1 unit is an emulsion consisting of 5 per cent soluble oil in the water. Tests for oil content, pH, sediment content, and iron content of this fluid have been recently initiated. Excessive oil content in the fluid not only causes foaming which in turn causes cavitation in the centrifugal pump, but also may result in an inversion of the emulsion.

The amount of oil consumed per month results in part from oil dissipation but is mainly due to loss through packing leaks and during well pulling operations. Hydraulic oil consumption records have been taken for each hydraulic unit since January, 1947, and the average consumption calculated from these data is shown in Table 4.

COMPARISON WITH BEAM PUMPING UNITS

Upon investigation it was found that there were 22 wells which had been converted from beam type to hydraulic units and had subsequently produced from the same zone long enough to afford a significant comparison. The wells were distributed between zones as follows:

Zone	No. of wells
Foix	2
Bell	1
Meyer	1
Buckbee	4
O'Connell	9
Clark	5
	22

The period investigated was from January, 1946, to September, 1948. The types of units installed in the wells can be summarized as follows:

Type	No. of wells
H1	1
H2	17
H3	4
	22

Gross Production

In most cases conversion from beam pumping units to hydraulic units results in a reasonable increase in gross production. In some wells the increase was due to increased plunger size, in others to lowering the pump, and in still others to the greater displacement available with the long-stroke unit. Examples can be found in the individual well data tabulated in Table 6, and the per cent change due to the installation of the hydraulic units is tabulated in Table 5.

Although the ability to produce large volumes of fluid is of great importance, particularly in competitive fields, economy and continuity of operation are essential in any pumping unit which is to have wide application. In an attempt to evaluate these factors the following data were collected for each well: (1) gross production lost

TABLE 5. Average well characteristics and unit performance by zones.

Items	Well production zones: Foix	Bell	Meyer	Buckbee	O'Connell	Clark
Number wells observed	2	1	1	4	9	5
Avg formation temperature, °F	128	137	148	174	190	198
Avg water salinity, G/G	300	350	750	1250	1400	1500
Avg oil gravity, °API	26.1	33.2	34.3	33.1	33.2	32.9
Avg per cent water	72.0	85.6	87.0	88.0	49.7	60.3
Avg production lost, B/D						
Beam type	1.5[△]	12.9[△]	13.3[△]	13.2	12.8	19.5
Hydraulic type	38.5	16.9[△]	7.0[△]	13.5	14.1	14.2
Avg daily man-hours*						
Beam type	0.467	1.185[△]	2.030[△]	1.364	1.440	2.794
Hydraulic type	2.036	1.126[△]	0.514[△]	1.056	1.040	1.489
Yearly rod breaks						
Beam type	0	2.7[△]	1.4[△]	8.9	11.7	10.5
Hydraulic types	0	0–4.1[+]	0[△]	0–9.7[a]	5.1	3.5–4.7[e]
Yearly pump changes						
Beam type	7.4	11.9	9.9	6.4	3.8	6.0
Hydraulic type	0[#]	13.2–5.1[†]	1.7	3.3	1.9	4.4

Note; *Man-hours include all maintenance and repair.
[△]Only one well observed.
[+]None for the production period with sucker rods and 4.1 with 1¼ inch tubing.
[a]None for H′ and 9.7 for one H_1.
[e]Average 3.5 for H2 unit and 4.7 for one H3.
[#]Less than one month record.
[†]13.2 for H3 unit with sucker rods and 5.1 with 1¼ inch tubing.

TABLE 6. Comparison of beam type and hydraulic type pumping units, Santa Fe Springs oil field.

Well; A Zone; Foix

Item	Beam type I	Hydraulic type II	Change, per cent I—II
Period	12-10-46 to 8-29-48	3-14-48 to 7-31-48	
Pump unit	B2b	H3	
Stroke length	54″	10′	
Pump	2½x1—¾x12	2½x2x20	
Pump depth, feet	3385	3378	
Pump speed, SPM	22	3.5	—34
Gross production, B/D	166	205	+24
Water cut, per cent	80.3	87.7	
Lost gross production, B/D	1.5	1.5	
*Daily man-hours	0.467	.637	+36
Pump changes/year	7.36		—100
Rod breaks/year			
Tubing jobs/year	1.64	5.3	+222

*MH/D represents total maintenance and repair jobs.

Well; B Zone; Foix

Item	*Gas lift I	Hydraulic type II	III	Change, per cent I—II	I—III	II—III
Period	1-6-46 to 6-30-47	7-23-47 to 8-5-47	8-6-47 to 8-31-48			
Pump unit	Intermitter	H3	H3			
Stroke length		10′	1′			
Pump	3″ Tbg.	3x2½x20	3x2½x20			
Pump depth, feet	3269	3534	3534			
Pump speed, SPM	3200G/O	4.7	4.7			
Gross production, B/D	149	195	220	+31	+48	+14
Water cut per cent	57.0	59.0	60.0			
Lost gross production, B/D	1.6	75.1	20.1	+100	+100	—73
**Daily man-hours	0.030	7.775	3.435	+100	+100	—56
Pump changes/year			2.8			+100
Rod breaks/year						
Tubing jobs/year			13.0			+100

*This is not a beam type of unit but for matter of interest, it is included.
**MH/D is total maintenance and repair.
In the III period the well was produced w/1¼″ tubing.

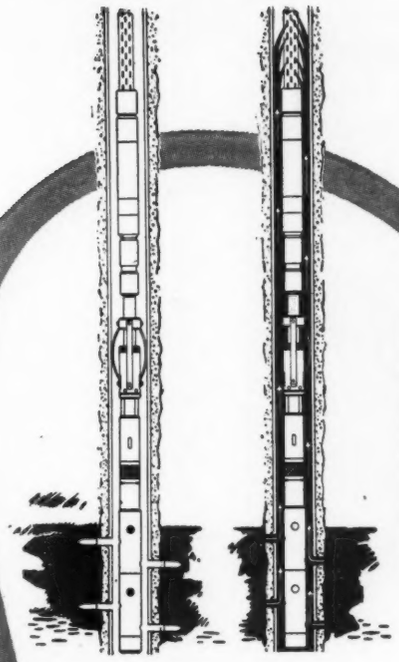


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TABLE 6. (Continued)

Well; C Zone; Bell

Item	Beam type I	Hydraulic type II	Hydraulic type III	Hydraulic type IV	Change, per cent I—II	Change, per cent I—III	Change, per cent I—IV
Period	1-1-46 to 10-2-46	10-3-46 to 2-4-47	2-5-47 to 7-27-47	8-8-47 to 7-31-48			
Pump unit	B_{2a}	H_3	H_3	H_3			
Stroke length	54″	10′	10′	10′			
Pump	3x2¼x10	3x2¼x14	3x2¼x14	3x2¼x14			
Pump depth, feet	3972	3972	3812	3812			
Pump speed, SPM	18	5.0	5.0	6.7	−72.2	−72.2	−62.7
Gross prod., B/D	273	271	317	285	−0.7	+16.1	+4.4
Water cut, per cent	80.0	83.8	87.2	91.5			
Lost gross prod., B/D	12.9	28.1	12.2	10.3	+117	−5.3	−20.1
*Daily man-hours	1.185	1.919	0.808	0.645	+62	−32	−46
Pump changes/year	11.92	11.67	14.75	5.08	−2	+24	−58
Rod breaks/year	2.65			4.07 (1¼″ Tbg.)	−100	−100	+56
Tubing jobs/year				1.02			

*MH/D is total maintenance and repair. During IV period well was produced with 1¼″ tubing.

Well; D Zone; Meyer

Item	Beam type I	Hydraulic type II	Hydraulic type III	Change, per cent I—II	Change, per cent I—III	Change, per cent II—III
Period	1-1-46 to 9-28-46	10-2-46 to 4-15-47	4-22-47 to 8-31-48			
Pump unit	B_{2a}	H_3	H_3			
Stroke length	54″	10′	10′			
Pump	2½x2x16	2½x2¼x15	*2½x2x17			
Pump depth, feet	4531	4512	3975			
Pump speed, SPM	23	6.5	6.3	−72	−73	−3
Gross production, B/D	211	266	254	+26	+20	−5
Water cut, per cent	85.0	89.0	89.0			
Lost gross production, B/D	13.0	6.4	7.6	−52	−42	+20
**Daily man-hours	2.030	0.530	0.498	−69	−75	−6
Pump changes/year	9.92	1.86	1.47	−81	−85	−21
Rod breaks/year	1.35			−100	−100	
Tubing jobs/year	4.03		0.73	−100	−82	+100

*Half time pump produced with 1¼″ plunger from 4366′ depth **MH/D represents total maintenance and repair jobs.

Well; E Zone; Buckbee

Item	Beam type I	Beam type II	Beam type III	Hydraulic IV	Change, per cent I—II	Change, per cent I—IV	Change, per cent II—III	Change, per cent II—IV
Period	1-1-46 to 7-5-46	8-2-46 to 4-30-47	5-1-47 to 1-17-48	4-16-48 to 6-28-48				
Pump unit	B_3	B_{1b}	B_{1b}	H_{2a} (Experi.)				
Stroke length	96″	66″	66″	15′				
Pump	2½x2x18	2½x2x18	2½x2x18	2½x2x31				
Pump depth, feet	5079	5079	5079	5079				
Pump speed, SPM	16	19	17	5.8	+19	−64	−11	−70
Gross production, B/D	306	297	273	346	−3	+13	−8	+17
Water cut, per cent	95.6	94.5	96.8	98				
Lost gross production, B/D	0	7.9	19.7	19	+100	+100	+100	+100
*Daily man-hours	.624	1.313	1.443	0.932	+100	+49	+10	−29
Pump changes/year	3.93	5.57	6.93		+42	−100	+24	−100
Rod breaks/year	7.85	9.75	9.71		+24	−100	−0.4	−100
Tubing jobs/year				5.0		+100		+100

*MH/D represents total maintenance and repair jobs.

Well; F Zone; Buckbee

Item	Beam type I	Hydraulic type II	Change, per cent I—II
Period	1-1-46 to 9-2-46	9-24-46 to 8-31-48	
Pump unit	B_3	H_{2a}	
Stroke length	96″	20′	
Pump	2½x2x18	2½x2½x31	
Pump depth, feet	5902	5895	
Pump speed, SPM	15	6	−60
Gross production, B/D	263	228	−13
Water cut, per cent	58.0	80.0	
Lost gross production, B/D	20.9	8.7	−59
*Daily man-hours	2.530	1.180	−53
Pump changes/year	9.68	3.60	−63
Rod breaks/year	12.45		−100
Tubing jobs/year		1.03	+100

*MH/D represents total maintenance and repair jobs. The two periods were produced with pump-off conditions.

Well; G Zone; Buckbee

Item	Beam type I	Beam type II	Hydraulic type III	Change, per cent I—II	Change, per cent II—III
Period	1-1-46 to 11-9-47	11-26-47 to 4-26-48	5-5-48 to 8-31-48		
Pump unit	*B_{1b}	*B_{1b}	H_{2a}		
Stroke length	66″	66″	20′		
Pump	2½x2x16	2½x1—¾x12	2½x2x31		
Pump depth, feet	6120	6110	6110		
Pump speed, SPM	20.5	19.0	6.0	−7	−68
Gross production, B/D	88	298	351	+240	+18
Water cut, per cent	94	96.2	96.0		
Lost gross production, B/D	5	29	13	+532	−56
**Daily man-hours	1.300	1.330	0.740	+2	−44
Pump changes/year	8.60	4.77	3.07	−45	−36
Rod breaks/year	3.77	7.15		+90	−100
Tubing jobs/year	0.54	2.39	3.07	+342	+28

*Part of production was pumped with Pacific 5FO.
**MH/D represents total maintenance and repair jobs. The well was repaired between periods I and II.

due to down time; (2) pulling jobs per year; and (3) total maintenance and repair man-hours per day, including the time of all rod crews and mechanics.

Down Time

It is of little value to increase the gross production rate from a well unless the well can be kept on production enough of the time to result in more oil in the tank at the end of the month. For this reason a study was made of the gross production lost due to down time. The results summarized in Table 5 indicate that there was no significant increase in this lost production when beam pumping units were replaced by hydraulic. Thus any increase in production rate resulting from the change should be reflected in the total production for the period.

Subsurface Repairs

Probably the most important factor in well operating costs is the frequency of pulling jobs. These jobs can be classified as (1) pump changes, (2) rod fishing jobs resulting from rod breaks, and (3) tubing jobs. A study was made of the pulling frequency and an attempt made to classify the work as outlined above. It can be seen from Table 5 that the frequency of pump changes has, in general, decreased after the installation of hydraulic units, with the greatest improvement occurring in the Meyer, Buckbee, and O'Connell wells. The higher frequency in the three shallow zones is due to sandy conditions in these wells.

It can also be seen that the frequency of rod breaks is generally lower for the hydraulic units, particularly in wells producing from the two deepest zones (O'Connell and Clark). The Bell Zone wells pumped with 1¼-in. tubing instead of sucker rods show a higher frequency of rod breaks, possibly due to the inadequacy of the joints from a fatigue strength standpoint.

The number of tubing jobs on most of the wells during the period studied was too small to permit significant comparisons to be made. There is no evidence of any change in the frequency of pulling tubing as a result of the installation of hydraulic units.

Total Maintenance and Repairs

The cost of operating a well is directly dependent upon the total man-hours expended on both surface and subsurface repairs and maintenance. In Table 6 total maintenance and repair man-hours per day are tabulated for the individual wells, while in Table 5 averages are shown for the different zones. Although the hydraulic

TABLE 6. (Continued)

Well; H Zone; Buckbee

Item	Beam type I	Hydraulic type II	Change, per cent I—II
Period	1-1-46 to 5-8-48	5-11-48 to 8-31-48	
Pump unit	B_{2c}	H_1	
Stroke length	72″	26′	
Pump	2½x1—¾x12	2½x1—¾x30	
Pump depth, feet	5444	5868	
Pump speed, SPM	17	5.0	—71
Gross production, B/D	301	437	+45
Water cut, per cent	86.6	88.0	
Lost gross production, B/D	9.8	16.6	+70
*Daily man-hours	1.010	0.867	—14
Pump changes/year	3.41		—100
Rod breaks/year	7.66	9.68	+26
Tubing jobs/year	0.43		—100

*MH/D represents total maintenance and repair jobs.

Well; I Zone; O'Connell

Item	Beam type I	Hydraulic type II	Beam type III	Hydraulic type IV	Change, per cent I—II	Change, per cent I—IV	Change, per cent II—IV
Period	1-1-46 to 4-5-46	4-13-46 to 8-12-46	8-14-46 to 9-10-46	11-23-46 to 3-24-48			
Pump unit	B_{1b}	*H	B_{1b}	H_{2a}			
Stroke length	66″	10′	66″	20′			
Pump	2½x1¾x12	2½x1¾x30	2½x1¾x30	2½x1¾x30			
Pump	2½x1¾x12	2½x1¾x30	2½x1¾x30	2½x1¾x30			
Pump depth, feet	6163	6742	6742	6742			
Pump speed, SPM	20.0	6.0	20.0	5.7	—70	—72	—5
Gross production, B/D	297	344	293	325	+16	+9	—6
Water cut, per cent	45.7	44.7	44.9	40.0			
Lost gross production, B/D	11.5	92.0	0.6	10.5	+100	—9	—89
**Daily man-hours	1.640	0.970	.045	0.156	—41	—91	—84
Pump changes/year	3.84	2.77		0.75	—28	—81	—73
Rod breaks/year	11.5				—100	—100	0
Tubing jobs/year	3.84				—100	—100	

*This hydraulic unit was operated in this well under experimental conditions.
**MH/D represents total maintenance and repair jobs.

Well; J Zone; O'Connell

Item	Beam type I	Hydraulic type II	Change, per cent I—II
Period	1-1-46 to 2-9-48	2-12-48 to 7-31-48	
Pump unit	B_{1a}	H_{2a}	
Stroke length	66″	20′	
Pump	2½x1¾x12	2½x2x30	
Pump depth, feet	6178	6813	
Pump speed, SPM	19.5	6.3	—68
Gross production, B/D	391	412	+5
Water cut, per cent	73.3	76.00	
Lost gross production, B/D	3.6	13.7	+286
*Daily man-hours	0.169	1.400	+728
Pump changes/year	0.47		—100
Rod breaks/year	1.89	2.03	+8
Tubing jobs/year		2.03	+100

*MH/D represents total maintenance and repair jobs.

Well; K Zone; O'Connell

Item	Beam type I	Hydraulic type II	Change, per cent I—II
Period	1-1-46 to 9-22-47	9-30-47 to 8-31-48	
Pump unit	B_{1a}	H_{2a}	
Stroke length	66″	20′	
Pump	2½x1¾x12	2½x2x30	
Pump depth, feet	6795	6780	
Pump speed, SPM	19	5.5	—71
Gross production, B/D	205	385	+88
Water cut, per cent	85.0	90.0	
Lost gross production, B/D	16.3	19.4	+19
*Daily man-hours	2.950	1.044	—65
Pump changes/year	5.79	4.33	—3
Rod breaks/year	15.64	6.50	—58
Tubing jobs/year	3.47		—100

*MH/D represents total maintenance and repair jobs. During Period I, bad tubing fishing job was performed.

Well; L Zone; O'Connell

Item	Hydraulic type I	Hydraulic type II	Change, per cent I—II
Period	1-1-46 to 12-13-47	12-20-47 to 8-31-48	
Pump unit	H	H_{2b}	
Stroke length	18″	20′	
Pump	3x1½	2½x2x30	
Pump depth, feet	6661	7107	
Pump speed, SPM	45	6.0	—87
Gross production, B/D	285	276	—3
Water cut, per cent	47.0	50.0	
Lost gross production, B/D	2.0	18.3	+814
*Daily man-hours	0.358	2.900	+710
Pump changes/year	3.59	4.28	+192
Rod breaks/year	None	9.97	
Tubing jobs/year		5.70	+100

*MH/D represents total maintenance and repair jobs.
For a matter of interest, a comparison of hydraulic units in this well was made.
An H_2 unit was installed because an H pump could not operate in a 4¾″ liner.
On 6-22-48, a complete string of new rods was installed in this well.

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TABLE 6. (Continued)

Well; M Zone; O'Connell

Item	Beam type I	Hydraulic type II	Change, per cent I—II
Period	1-1-46 to 5-18-48	8-20-48 to 8-31-48	
Pump unit	B_{2c}	H_{2a}	
Stroke length	60"	20'	
Pump size	2½x1½x12	2½x1¾x30	
Pump depth, feet	6775	6775	
Pump speed, SPM	15	5.6	—63
Gross production, B/D	237	290	+22
Water cut, per cent	10.0	10.1	
Gross production loss, B/D	6.5		None
*Daily man-hours	0.892		None
Pump changes/year	4.20		None
Rod breaks/year	4.20		None
Tubing jobs/year			None

*MH/D represents total maintenance and repair jobs.

Well; N Zone; O'Connell

Item	Beam type I	Hydraulic type II	Change, per cent I—II
Period	1-1-46 to 4-5-48	4-9-48 to 8-31-48	
Pump unit	B_{1a}	H_{2a}	
Stroke length	66"	20'	
Pump size	2½x1½x12	2½x2x30	
Pump depth, feet	6808	6801	
Pump speed, SPM	19.5	5.0	—74
Gross production, B/D	249	393	+58
Water cut, per cent	62.0	64.0	
Gross production loss, B/D	4.1	1.9	—53
*Daily man-hours	.249		
Pump changes/year	4.42		
Rod breaks/year	4.42		
Tubing jobs/year	0.44		

*MH/D represents total maintenance and repair jobs.

Well; O Zone; O'Connell

Item	Hydraulic type I	Beam type II	Hydraulic type *III	Change, per cent I—II
Period	1-1-46 to 5-21-47	7-28-47 to 7-13-48	7-15-48 to 8-31-48	
Pump unit	H	B_{1b}	H_{2a}	
Stroke length	18"	66"	20'	
Pump	2½x1¼	2½x1½x12	2½x1½x30	
Pump depth, feet	6976	6633	6590	
Pump speed, SPM	45	17.9	4.2	—60
Gross production, B/D	75	137	153	+81
Water cut, per cent	80.0	80.0	78.0	
Lost gross production, B/D	0.4	23.3		+5120
**Daily man-hours	0.347	3.260		+840
Pump changes/year	2.89	11.41		+295
Rod breaks/year	None	3.11		
Tubing jobs/year	2.16	8.30		+284

*This well's history is not long enough for comparison.
**MH/D represents total maintenance and repair jobs.
During period II, the well was reperforated and produced from 6562' for some time.
Between period I and II, the well was idle for two months.

Well; P Zone; O'Connell

Item	Beam type I	Hydraulic type II	Change, per cent I—II
Period	4-26-47 to 6-15-47	6-17-47 to 8-31-48	
Pump unit	B_{1b}	H_{2a}	
Stroke length	66"	20'	
Pump	2½x1¾x12	2½x2x31	
Pump depth, feet	6667	6667	
Pump speed, SPM	18.0	6.0	—67
Gross production, B/D	412	436	+6
Water cut, per cent	31.0	31.8	
Lost Gross production, B/D	4.0	29.3	+583
*Daily man-hours	.941	1.065	+13
Pump changes/year		3.98	+100
Rod breaks/year		7.96	+100
Tubing jobs/year			

*MH/D represents total maintenance and repair jobs.

Well; Q Zone; O'Connell

Item	Beam type I	Beam type II	Hydraulic type III	Beam type IV	Hydraulic type V	Hydraulic type VI	Change, per cent I—II	I—V	I—VI	V—VI
Period	5-21-46 to 3-9-47	3-11-47 to 9-22-47	9-23-47 to 10-7-47	10-8-47 to 11-4-47	11-5-47 to 1-17-48	1-26-48 to 8-31-48				
Pump unit	B_{1b}	B_{1b}	H_3 (Experi.)	B_{1b}	H_3 (Experi.)	H_{2a}				
Stroke length	66"	66"	10'	66"	10'	20'				
Pump	2½x1¾x10	2½x1¾x12	2½x1¾x12	2½x2x30	2½x2x30	2½x2x30				
Pump depth, feet	6666	6761	6760	6760	6760	6760				
Pump speed, SPM	21.5	20.0	6.0	20.0	6.0	6.0	—7	—72	—72	
Gross prod., B/D	453	456	406	343	477	516	+0.7	+5	+14	+ 8
Water cut, per cent	30.0	27.0	28.1	28.1	29.3	30.0				
Lost gross prod., B/D	7.8	23.3	69.6	8.6	43.1	7.5	+200	+456	—3	—83
*Daily man-hours	0.805	2.085	5.220	2.640	2.480	0.745	+159	+208	—8	—70
Pump changes/year	4.98	7.45	26.1	13.1			+50	—100	—100	
Rod breaks/year		33.5			24.7	4.97	+100	+100	+100	—80

*MH/D represents total maintenance and repair jobs.
This well was cleaned out between period I and II.

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units seem generally to require the expenditure of somewhat fewer man-hours, the difference is not as great as would be anticipated from the relation between pulling frequencies for the two types of units. This discrepancy is largely due to the relatively large number of man-hours expended in repairing the hydraulic units. Since these units are relatively new in the oil fields, it is anticipated that repair costs will decrease as the design of the units is perfected and as field personnel become more familiar with this type of equipment.

Conclusions

In evaluating the data shown in Tables 5 and 6, it must be remembered that in many wells other changes were made at the same time that the hydraulic units were installed. These changes undoubtedly affect the comparative performance of the two types of units. For instance, increased plunger size and increased pump depth might be expected to affect the pulling frequency adversely while the replacement of a rod string might be expected to reduce rod failures irrespective of the type of unit involved.

Despite these uncertainties it is thought that the results of these comparisons have at least limited significance. On the average it appears that rod failures were reduced 25 per cent, pump changes 50 per cent and total repair and maintenance man-hours 26 per cent by the installation of hydraulic pumping units.

It can be concluded from this study that hydraulic units are still to some extent experimental, since it seems likely that packing design and reversing mechanisms could be improved. On the whole, however, the units perform satisfactorily under rather adverse conditions. The principal advantage seems to be the long stroke attainable, which makes possible the use of slower speeds. This combination of stroke and speed makes it possible to pump greater volumes from some wells, particularly if it is necessary to pump appreciable volumes of gas along with the oil and water.

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Well; R Zone; Clark

Item	Beam type I	Hydraulic type II	Hydraulic type III	Hydraulic type IV	Change, per cent I—II	Change, per cent I—III	Change, per cent I—IV
Period	1-1-46 to 4-17-46	4-21-46 to 9-29-46	10-10-46 to 6-26-48	6-27-48 to 7-31-48			
Pump unit	B_3	B_3	H_{2a}	H_{2c}			
Stroke length	96″	96″	20′	20′			
Pump size	2½x1½x15	2x1¼x15	2½x1½x31	2½x1½x31			
Pump depth, feet	7721	7913	7878	7742			
Pump speed, SPM	15	15	6.0	6.0		−60	−60
Gross production, B/D	245	190	273	258	−22	+11	+5
Water cut, per cent	50.2	32.0	38.7	56.3			
Lost gross production, B/D	26.4	11.7	12.5	36.8	−56	−53	+39
*Daily man-hours	3.510	1.085	1.672	2.630	−69	−52	−25
Pump changes/year	6.82	4.51	2.34		−34	−66	−100
Rod breaks/year	34.1	**9.0	7.59	16.6	−74	−73	−51
Tubing jobs/year			0.58	5.53		+100	+100
Unit repairs/year	13.65		1.75		−100		−100
Total jobs/year	47.7	13.51	12.85	22.1	−72	−73	−54

*MH/D represents total maintenance and repair jobs.
**Some new rods were put on the rod string during this period.

Well; S Zone; Clark

Item	Beam type I	Hydraulic type II	Hydraulic type III	Hydraulic type IV	Change, per cent I—II	Change, per cent I—III	Change, per cent I—IV
Period	*1-1-46 to 4-30-46	5-5-46 to 9-20-46	9-21-46 to 3-21-47	3-22-47 to 8-31-48			
Pump unit	B_{1a}	H_{2a}	H_{2a}	H_{2a}			
Stroke length	66″	20′	20′	20′			
Pump size	2½x1½x12	2½x1¾x27	2½x1½x27	2½x1½x27			
Pump depth, feet	7089	7906	7239	7177			
Pump speed, SPM	17	5.8	5.5	5.6	−66	−68	−67
Gross production, B/D	245	220	247	285	−10	+1	+16
Water cut, per cent	53.9	64.0	63.5	56.0			
Lost gross production, B/D	1.4	8.9	23.1	7.0	−517	+1515	+3890
**Daily man-hours	0.067	.720	3.100	.812	+975	+9530	+1112
Pump changes/year		2.63	10.00	1.38	+100	+100	+100
Rod breaks/year		2.63	24.00	1.38	+100	+100	+100
Tubing jobs/year			4.00	1.38		+100	+100

*This period is very short for fair comparison.
Δ¼″ rods were replaced by new rods during this period.
**MH/D represents total maintenance and repair jobs.

Well; T Zone; Clark

Item	Hydraulic type I	Hydraulic type II	*Change, per cent
Period	1-1-46 to 3-21-47	10-25-47 to 8-31-48	
Pump unit	H_3	H_3	
Stroke length	10′	10′	
Pump size	2x1½x20	2x1½x20	
Pump depth, feet	6836	7205	
Pump speed, SPM	6.5	7.0	
Gross production, B/D	111	100	
Water cut, per cent	75.0	85.5	
Gross production loss, B/D	8.2	10.8	
**Daily man-hours	1.415	1.102	
Pump changes/year	7.38	4.68	
Rod breaks/year	8.20	1.17	
Tubing jobs/year	0.82		

*Not enough record obtained in this well for comparison; between periods well remained idle.
**MH/D represents total maintenance and repair jobs.

Well; U Zone; Clark

Item	Hydraulic type I	Hydraulic type II	Hydraulic type III	Change, per cent I—II	Change, per cent I—III
Period	*1-1-46 to 1-29-47	2-7-47 to 8-19-47	8-27-47 to 8-31-48		
Pump unit	H	H	H_{2b}		
Stroke length	18″	18″	20′		
Pump size	3½x1½	3½x1½	2½x2x30		
Pump depth, feet	7228	7585	7917		
Pump speed, SPM	50	50	4.5		−91
Gross production, B/D	295	177	310	−40	+5
Water cut, per cent	62	80	90		
Lost gross production, B/D	5.3	1.8	22.5	−65	+329
**Daily man-hours	0.426	0.577	1.737	+35	+308
Pump changes/year	2.78	5.64	5.90	+103	+112
Rod breaks/year			0.98		+100
Tubing jobs/year			0.98		

*During the I period, a hydraulic pump operated inside of 6⅝″ casing, and during II period it operated inside of 4¾″ liner. Between these periods, the well was cleaned out.
**MH/D represents total maintenance and repair jobs.

Well; V Zone; Clark

Item	Beam type I	Hydraulic type II	Change, per cent I—II
Period	1-1-46 to 8-7-46	8-21-46 to 8-31-48	
Pump unit	B_{1b}	H_{2a}	
Stroke length	66″	20′	
Pump size	2½x1½x15	2½x1¾x30	
Pump depth, feet	7847	7713	
Pump speed, SPM	16.5	5.0	−70
Gross production, B/D	247	288	−16
Water cut, per cent	57.8	65.0	
Gross production loss, B/D	20.3	9.7	−52
*Daily man-hours	3.290	1.242	−62
Pump changes/year	6.66	4.43	−33
Rod breaks/year	20.00	2.95	−85
Tubing jobs/year	5.00	0.49	−90

*MH/D represents total maintenance and repair jobs.

Field Control of

Oilfield Pumping Equipment†

J. N. GREGORY*

The conditions faced by an oil producer in accomplishing continuous operation of surface pumping equipment without frequent attendance are outlined. The construction and application of devices to perform routine services on oil well pumping equipment are described and particular attention is directed toward eliminating the services which ordinarily must be performed at frequent intervals. The need for a preventive maintenance program is outlined and the instruments and tools which may be used in such a program are explained. Certain devices for use at problem wells are discussed, and the value of operating procedures which consider routine service, preventive maintenance, and corrective measures is indicated.

PRODUCING crude oil is unusual if it is compared with the usual production or assembly line of a manufacturing industry. The products are fluid and can be moved without manual handling, and there is no control of the quality of the product as it issues from the ground, on the other hand, the "production line" cannot be placed in an advantageous location nor arranged to make operation simple. Instead, oil is where you find it, and the oil producer encounters difficult terrane, adverse climate, widely spaced wells, and varied well conditions which pose many problems unique to the oil industry. It is the intent of this discussion to describe some of the devices and programs which are effective in accomplishing continuous operation without breakdown or excessive servicing and maintenance costs.

Oil wells may be considered to fall into one of three categories; wells which should produce to capacity continuously, stripper wells which will produce to capacity without continuous operation, and wells with an allotment which is less than the productive capacity. Of these, the first are of the most concern since full time operation at capacity is necessary if the greatest ultimate yield is to be realized, and to the cost of making repairs must be added the loss that may occur when production ceases. Thus the operator must select equipment capable of producing the well to capacity with enough allowance for normal wear that an excess amount of time will not be required to replace worn parts, and he must also organize a service and maintenance routine which will assure continuous operation efficiently.

Continuous operation is not always necessary. In some fields the ability of the oil sands to give forth their contents is so limited that the capacity may be produced by intermittent operation, and careful planning will permit this to be done efficiently. If a field is produced at a lower rate than capacity, intermittent operation may be economical, however, the effect of a shut-down must be considered since many wells will be harmed if water enters the producing zone.

If down time through failure is to be avoided, equipment must be kept

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FIG. 1. Throttle control actuated by intake manifold pressure.

FIG. 2. Radiator water level float control.

Fig. 3. Crankcase oil level float control.

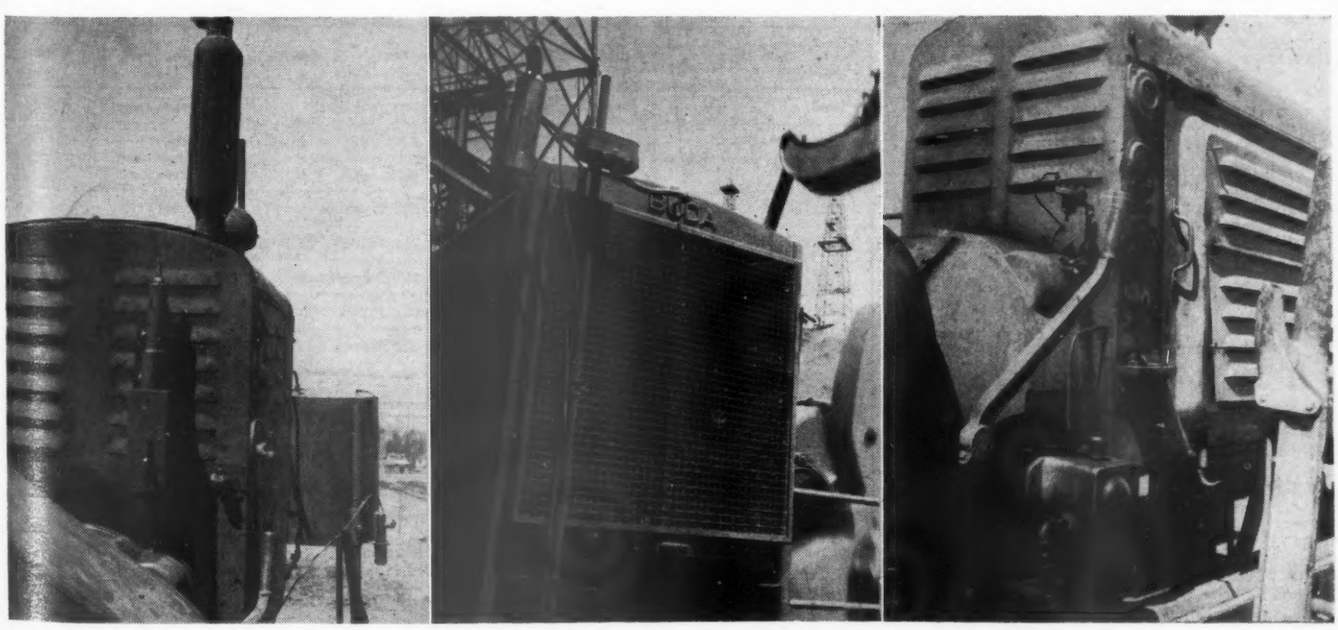


FIG. 4. Crankcase oil level vacuum control.

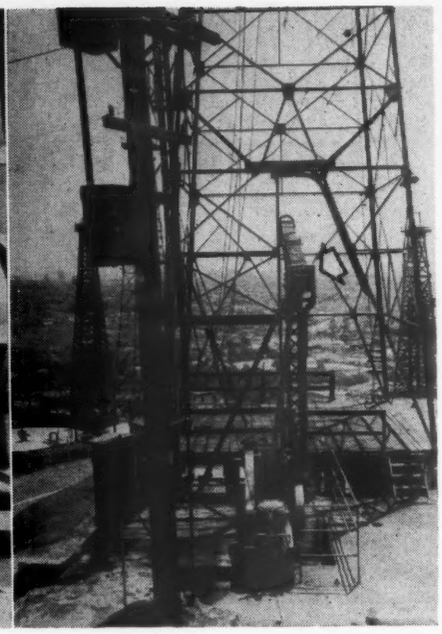


FIG. 5. Application of graphite impregnated plastic oil-less bearing.

in good operating condition and imminent failure should be determined before a breakdown occurs. Three types of maintenance and repair service are required if the surface equipment is to be kept in first-class shape: routine service at frequent intervals to determine that the wells are pumping properly, to perform miscellaneous services such as adding oil and water to gas engines and lubricants to bearings, and to gauge production rates; preventive maintenance at infrequent intervals to determine engine performance and to inspect for worn or loose parts which may result in breakdown; and repair work as required to overhaul engines and replace faulty parts. There is no master plan which may be adopted to fit all conditions or fields, but if adequate preventive maintenance is inaugurated and devices are installed to do as much of the routine services as practical, it will be found that the time and work involved in pumping and down-time from failure will be relatively small. There are a number of devices which have been developed to perform various services on oil well pumping equipment, and they are listed with a brief description of their construction and function without regard to the novelty or desirability of exact application.

Speed Regulation

If the maximum production is to be realized without excessive over-pumping, close speed regulation is necessary. Electric motor drives pose no problem other than proper design, since the induction motor is essentially constant speed. They do have the disadvantage that the speed cannot be readily adjusted to changing conditions. Gas engines equipped only with maximum speed governors need frequent checking; the throttle must be adjusted manually to the desired speed and the setting may tend to change over a period of time. Also, until stable pumping conditions are reached, return trips to adjust the throttle may often be necessary. A device known as a "Vacontrol" has been developed to correct this. The "Vacontrol" is a throttle control actuated by the intake manifold pressure. It consists of a cylinder piped to the intake manifold, and a piston connected through a linkage to the throttle. An adjustable spring controls the movement of the piston, and a lag valve placed between the cylinder and the intake manifold dampens the fluctuations in pressure which tend to make

FIG. 6. Diagram of automatic counterbalance.

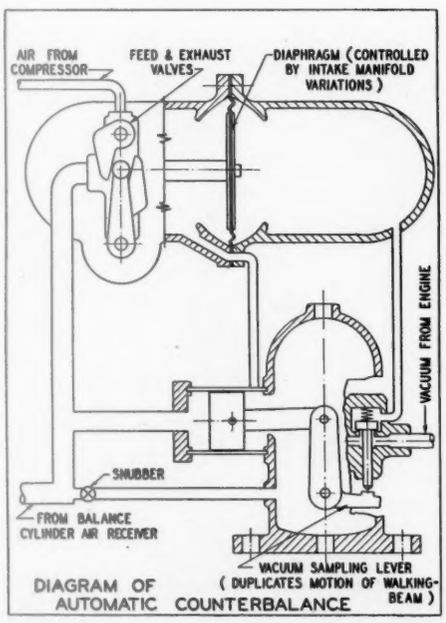

AIR FROM COMPRESSOR
FEED & EXHAUST VALVES
DIAPHRAGM (CONTROLLED BY INTAKE MANIFOLD VARIATIONS)
VACUUM FROM ENGINE
SNUBBER
FROM BALANCE CYLINDER AIR RECEIVER
VACUUM SAMPLING LEVER (DUPLICATES MOTION OF WALKING-BEAM)
DIAGRAM OF AUTOMATIC COUNTERBALANCE

FIG. 7. Preventive maintenance check list.

Unit No._____ PUMPING UNIT AND GAS ENGINE SERVICE MEMORANDUM Date_____

Location_____ By _____

Work Symbols: 00 = Examine: O = Repair: X = Adjust + = Renew: – = Clean

Head	Gear Box	Compression:	Carburetor
Cylinders	High Speed Shaft	#1 #2 #3	Regulator
Pistons	Low Speed Shaft	#4 #5 #6	Air Cleaner
Pins	Brake	Oil Pressure	Governor
Rings	Idler Pulley	Oil Switch	RPM
Rods	Crosshead Bearing	Oil Temperature	Vacuum-load
Main Bearings	Outboard Bearing	Oil Filter	Vacuum-Idle
Crank Shaft	Drive Belts	Oil Screen	Radiator
Cam Shaft	Wrist Pin	Oil Change	Water Temp.
Oil Pump	Pitman Bearings	Oil Consumption	Water Pump
Timing Gears	Sampson Post Bearing	Magneto	Fan
Valves	Walking Beam	Spark Plugs	Fan Belt
Muffler	Horsehead Cable	Wiring	Hose
Clutch	Base & Fndtn. Bolts	Starter	Lube Motor
	Housekeeping	Generator	Lube Pumping Unit

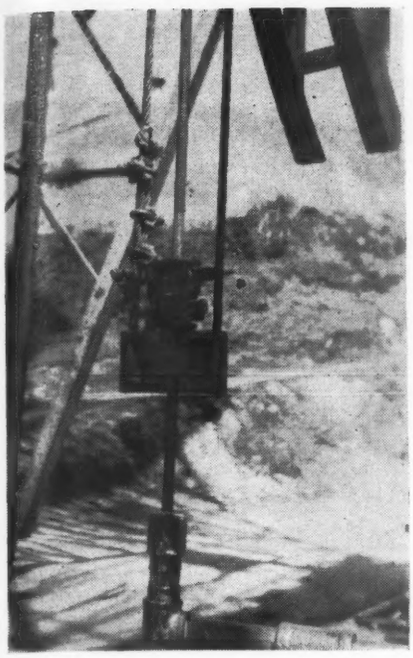


FIG. 8. Horsehead cable secured with wire line clamps.

the control surge. An idling screw and manual control lever complete the assembly.

It is the purpose of the control to adjust the throttle by the load instead of by the speed as is done with a conventional governor. In normal operation the spring is adjusted so that when the plunger is at the extreme end of its travel, the throttle for pulling the maximum load expected is obtained, thus any reduction in load will reduce the throttle. If the load is properly balanced, there will be no movement of the throttle; if not, the throttle will be adjusted to load changes as they occur. If extreme unbalance exists, the lag valve prevents the piston from moving rapidly enough to keep up with the changing load and the engine will die.

The "Vacontrol" serves four purposes:

1. It smooths out erratic motion.
2. It serves as a safety shut-off when the load becomes unduly out of balance.
3. It permits the engine to be declutched and re-engaged without manually adjusting the throttle to the proper operating speed.
4. If a well has been shut down and must be pumped up (such as occurs after a pulling job), the Vacontrol will adjust the throttle to the load automatically until stable conditions are reached. This avoids return trips to the well to adjust the engine speed.

Lubricating and Cooling Systems

The regularly equipped gas engine requires frequent additions of oil and water. When the work is performed manually, there is a tendency to overfill the crankcase, which is wasteful in itself, and although the time involved in servicing one engine may be small, collectively a number of engines consume a surprising amount of time. A practice which is becoming widespread is the storage of adequate amounts at each engine so oil and water can be added automatically, maintaining constant levels. There are suitable float valves available for this purpose; one of them suitable for the control of water in the radiator is a humidifier control valve which is snap acting and self cleaning. Working parts of the valve are above the water level to reduce corrosion and scale accumulation. An oil float valve has been developed specifically for maintaining an accurate oil level, equipped with a screen filter, visible sludge chamber, sight glass, and vacuum breaker for engines which operate with a vacuum in the crankcase.

Another type is a vacuum controlled oil level regulator. It consists of an air tight drum, piped from the bottom to the engine crankcase. An air vent tube connected to the top is adjusted so its free end touches the oil at its proper level. When the level drops below the vent tube opening, air is admitted to the top of the drum, allowing oil to drain into the crankcase until the vent tube opening is closed by the oil surface. Vacuum from the intake manifold connected to the top of the drum, with a restrictor, draws a very small quantity of air continually through the air vent tube. This compensates for atmospheric temperature changes and draws any excess of oil which might find its way into the crankcase back into the drum.

Such devices, and the storage of an adequate quantity of lubricating oil at the well, eliminate the time-consuming addition of oil and water at frequent intervals and tend to reduce oil consumption and contamination.

FIG. 9. Crankcase oil analysis chart.

NATURAL GAS AND BUTANE ENGINE REPORT

-2-

FABER Laboratories

NEUTRAL—to brands and products.
IMPARTIAL—to buyer and seller.
UNBIASED—opinions and analyses.
LABORATORIES serving from CANADA TO MEXICO COAST TO COAST

November 19, 1947

ENGINE NUMBER	ENGINE SLUDGE INDEX	SOLIDS VOLUME	FABER VIS. COSITY	FOREIGN MATTER: METAL	WATER	GUMS, TARS, RESINOUS	FUEL SOOT	FREE CARBON	DIST. SAND	ANALYSIS: OPERATING S.A.E. NUMBER	SEE REVERSE SIDE	PERIOD THIS OIL RAN	PERIOD NEXT SET	VIS. ABASH	OIL ADD
34	0.2	0.2	272	Trace	X	X	X	X	X	30		45 days		12/15	
Columbia														11/19/47	
37	0.2	0.2	264	X	Water	X	X	X	X	30	#6	30 days	Drain now	12/15	
Columbia				Low crankcase temperature.						Change oil.				11/19/47	
Fisher 3	0.2	0.2	304	X	X	X	X	X	X	Light 40		171 days		1/15/48	
														11/19/47	
4	0.2	0.2	280	X	X	X	X	X	X	30		280 days		1/15/48	
Fisher														11/19/47	
5	0.2	0.2	280	X	X	X	X	X	X	30		338 days		1/15/48	
Fisher														11/19/47	
6	0.2	0.2	280	Trace	X	X	X	X	X	30		51 days		1/15/48	
Fisher														11/19/47	

RED DENOTES ABNORMAL SLIGHT IS BORDERLINE BELOW ABNORMAL TRACE IS BORDERLINE ABOVE NORMAL X NOT PRESENT OR NOT SUFFICIENT TO MENTION

FIG. 10. Radiator shutters.

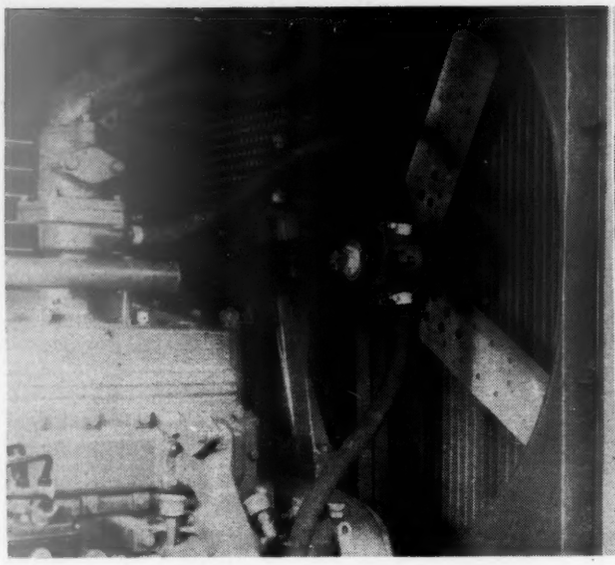


FIG. 11. Thermally controlled variable pitch fan.

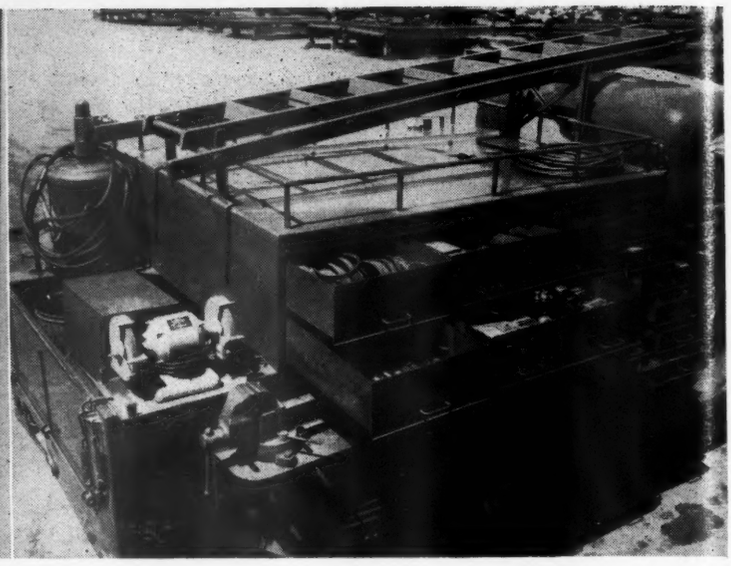


FIG. 12. Fully equipped tool truck.

Bearings

Properly designed bearings in the pumping unit may go without service for long periods of time if an adequate oil reservoir is built into the bearing assembly and oil seals are maintained. A bearing requiring no lubrication has been used in some areas with success. It consists of a graphite impregnated plastic block with a long fibre asbestos binder, molded under 6000 psi. Its compressive strength is some 11,500 psi determined on a 3-in. unsupported cube, and it has a Brinell hardness of about 84. Some of these have been in use for eight years without failure or measurable wear, their particular use in oil field equipment being confined to the overhead members such as the upper pitman and sampson post bearings which are difficult to lubricate.

Automatic Shut-Offs

If a pumping unit is to operate without frequent service and inspection, safety devices to shut the unit down in the event of failure are as necessary as devices to eliminate frequent lubrication. Electric motors may be protected with overload heater relays, although a more foolproof and sensitive device is the "Thermoguard" which consists of a thermostatically operated switch built into the motor winding. It has the advantage of breaking the circuit if the motor itself overheats from any reason such as fire or "single phasing."

Gas engines may be protected by oil pressure and thermostatically controlled switches which shut the engine down in the event necessary engine auxiliaries fail. Other shut-offs, such as inertia switches on walking beams and pressure operated switches on air counterbalance units, are also available.

Stripper wells which operate part time may be shut down by clockwork if they may be operated on a fixed schedule. Another device which has found some application consists of a bucket on a switch lever hung under the outlet of the flow line. A small hole in the bottom permits oil to flow out, but at a slower rate than it enters if the well is pumping. When the well pumps off, the bucket empties and opens the switch controlling the prime mover.

Automatic Starters

Stripper wells which operate part time may be started by clockwork if they are pumped electrically. In general, a group of wells operated under this system should be operated on a staggered schedule in order to keep the power demand low.

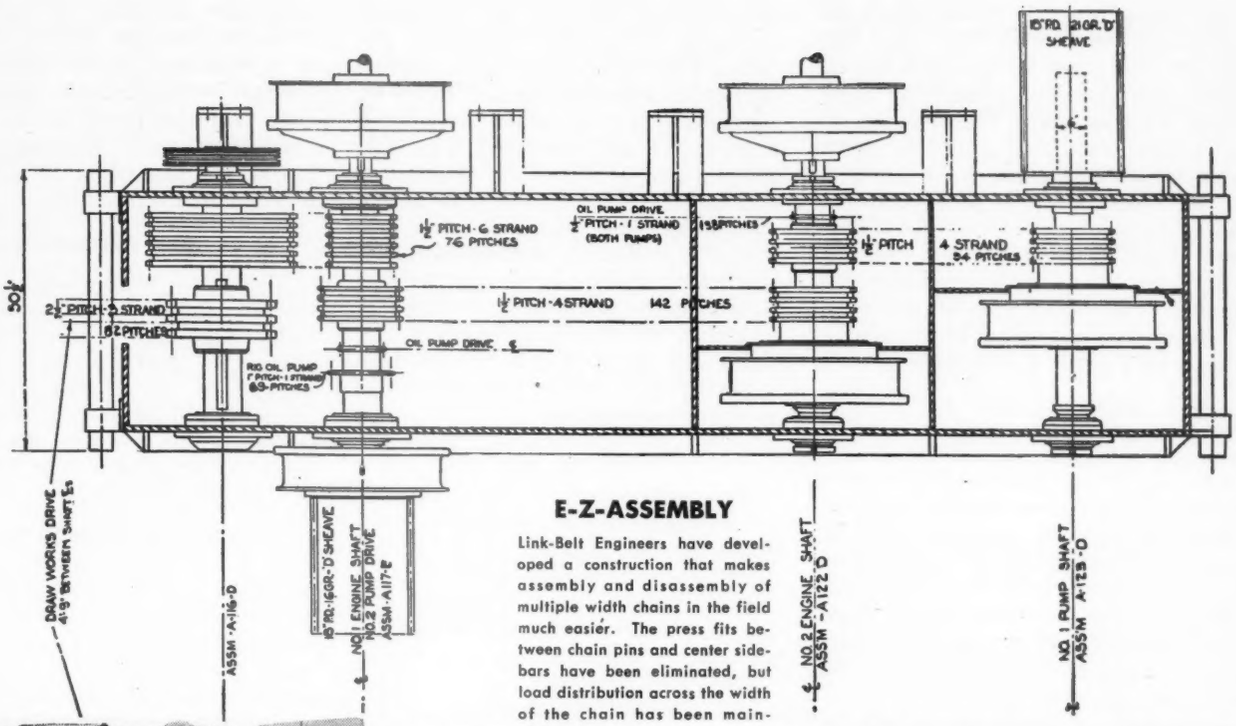
Power failure, even for short duration, will shut down an electrically operated lease. If the linestarters are connected to start the motors when the current comes back on, the high starting currents may be too severe for the power system. To prevent this, delay switches must be used. Several types are available. Among the more common are motor driven cams, dashpots, and thermostats. In each, the principle is to delay the application of current to the holding coil for a predetermined time after the circuits have been energized. No known attempts to start gas engines automatically have been made. It is doubtful that automatic engine starting will ever find much application, since shut downs usually indicate trouble in the unit itself.

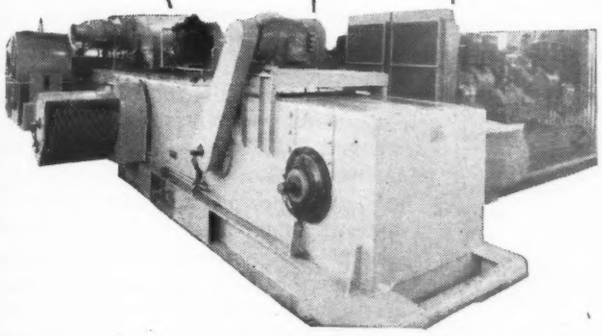
Counterbalancing

The need for proper counterbalancing is accentuated if close attention is paid to economical equipment selection and operation. The need for readily variable counterbalancing does not appear to be universal, but certain wells cause trouble of this nature, and it is interesting to note that an automatic counterbalance has been developed which is easily adapted to any air counterbalanced unit. With a gas engine prime mover, two chambers connected through a timing valve to the engine manifold are used. The timing valve is actuated so one chamber is exposed to the manifold pressure during part of the upstroke, the other during the counterpart of the downstroke. If perfect counterbalance exists, the pressures in the two chambers are equal; if not, a diaphragm between the two chambers actuates a valve in the air counterbalance system, varying the pressure until proper balance exists. If an electric motor drive is used, solenoids are substituted for the vacuum chambers. One of these devices has demonstrated its ability to maintain proper balance even when the polish rod parted.

Trouble Calls

It would be ideal if it were never necessary to visit a well which was



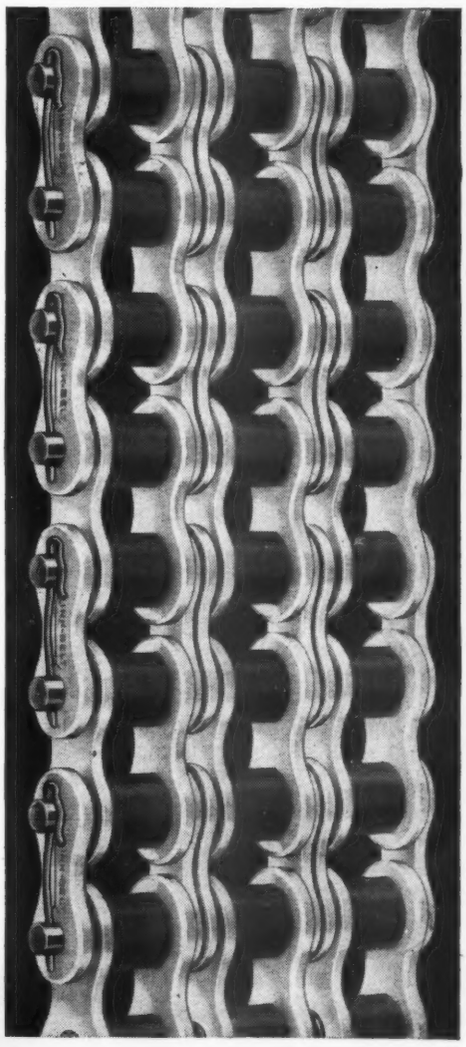


E-Z-ASSEMBLY

Link-Belt Engineers have developed a construction that makes assembly and disassembly of multiple width chains in the field much easier. The press fits between chain pins and center sidebars have been eliminated, but load distribution across the width of the chain has been maintained.

● ● ●

Compound drive for Turney Rig 1250. Link-Belt Silverlink Roller Chains are completely enclosed in dust proof forced-feed oil bath.



TURNEY RIGS USE LINK-BELT ROLLER CHAINS . . . AS *Standard Equipment!*

Today's high-speed drilling, heavier loads and greater depths have made Link-Belt Silverlink Roller Chain the *first choice* of oil operators and equipment manufacturers.

That's why Turney now uses Link-Belt Silverlink as standard equipment on their Super 1250 Rig. On their power drive assembly you'll find two 1½" pitch RC-120-4 quad chains on the compound . . . one 2½" pitch RC-200-3 triple chain and one 1½" pitch RC-120-6 sextuple chain on the input transmission drives . . . as well as other Link-Belt chains.

The compound drive shown here was recently built by Hunt Tool Company for the Turney Manufacturing & Engineering Company. It is now being used by a major oil company to power a Turney rig drilling an off-shore well. And everyone—including Link-Belt—is proud of the job!

When you decide it's *long life with low maintenance* you're after—always specify Link-Belt as *your* standard equipment. It's been helping to make hole in fields around the world since the advent of rotary.

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11,469

performing properly. Achievement of such a goal in the near future does not appear likely, but an approach lies in radio transmission, which has been tried in certain areas. Transmission of all performance data would be quite complex, so efforts have been confined to the transmission of poor performance. An arbitrary selection of standards is made, and transmission occurs only when the standards are not maintained. The signal transmitted only indicates that failure has occurred and that a visit to the well is necessary.

The equipment has three components: an initiator such as a pressure gauge with electrical contacts set at the upper and lower limits of satisfactory values; a transmitter having a crystal controlled oscillator and a tone modulator; and a crystal controlled super-heterodyne receiver equipped with decoding and indicating devices. The keying mechanism in the transmitter is automatic in its cycle, which requires a maximum of five seconds, and 400 combinations of pulses are possible. The short transmission time and remote likelihood that two wells will fail simultaneously allow as many as 400 wells to be controlled. The receiver, with its filters, relays, and decoding devices, may signal with lights, buzzers, or graphically.

Such radio transmission has been used to indicate pressures at flowing wells and gas engine performance sucessfully, and offers promise in controlling wells which are subject to failure when conditions change.

Preventive Maintenance

If pumping equipment is to operate without failure, a well planned preventive maintenance program must be devised. Particularly, if frequent servicing is limited to the very cursory inspection made possible by the devices outlined above, the entire mechanism should be thoroughly serviced and inspected at infrequent but regular intervals. Experience indicates that such intervals may be extended to as much as two months, although when it is realized that a period of 1400 hours is equivalent to some 40,000 miles of ordinary automobile operation, the need for service that is thorough is apparent.

Preventive maintenance should include inspection of all parts of the machinery; lubrication of all wearing surfaces; adjustment, repair or renewal of faulty parts such as bearings, clutches, belts, horsehead cables, and ignition and cooling, and lubricating systems; testing of engine conditions to determine performance; and a report of all services performed and conditions noted to allow an intelligent appraisal of the need for major repairs. The value of a written report cannot be overemphasized. It serves as a check list to assure that all necessary services are performed and at proper intervals, reports poor operating conditions which call for a change in equipment, and provides a history useful in evaluating performance and need for repairs. A simple service memorandum is sufficient, and the desirability of recording most of the services is apparent, however, discussion of a few of them with the tools used may be pertinent.

Horsehead Cables

The usual horsehead cable, babbitted to the carrier bar, may give considerable trouble in a corrosive atmosphere if it does not have proper care. Periodic lubrication will lengthen the life, and a galvanized cable is now on the market which promises to resist corrosion. At best, the wire line adjacent to the babbitted socket is subject to early failure due to the effect of heat while attaching the socket. One carrier bar now available avoids this. It is so formed that the wire line may be carried around it in back of the polish rod while maintaining a vertical pull to avoid bending in the polish rod. Thus the horsehead cable may be made continuous by joining the two ends with wire line clamps. Cables so installed are easily replaced, and by moving them from time to time, bending fatigue in one spot may be reduced and the life increased.

Fuel Adjustment

The carburetor adjustment is quite important. On natural gas, an engine with a lean mixture sounds smooth and sweet, but it will be found that the excess oxygen and high cylinder temperatures will burn valves and oil and clog the ring slots. Temperatures may be reduced appreciably, avoiding this trouble, if the carburetor is adjusted to an air-fuel ratio of about 12.8 to 1. An exhaust gas analyzer is the most practical method of determining this. One of the types which is rugged and easy to use is an instrument using the thermal conductivity principle. In this, two spirals of platinum wire are enclosed in separate cells encased in a solid metal block to insure equal temperatures. One cell is filled with a standard gas with known characteristics. The exhaust gases are passed through the other cell. Each coil forms one arm of a Wheatstone Bridge through which a constant current flows, heating the spirals. The loss of heat through the gases surrounding the spirals is dependent on the thermal conductivity of the gases, so by measuring the resistance the temperature difference may be determined which is a measure of the difference in thermal conductivities. The air-fuel ratio is proportional to the thermal conductivity so the Wheatstone Bridge galvanometer reading is a direct indication of the mixture.

Engine Performance

The speed of the engine is measured to determine if it lies in the optimum range, and from vacuum readings the horsepower may be determined. The finest maintenance program will be of little avail if engines are not properly loaded, and improper application may be the key to many engine failures.

The water temperature, oil temperature, oil consumption, and compression values are excellent guides to engine wear. Another tool with considerable value is a periodic analysis of the crankcase oil. Samples are withdrawn from the bottom of the crankcase and analyzed for such properties as viscosity, sludge, water content, and foreign matter from which may be determined high piston temperatures, clogged oil ring slots, dirty air cleaners and oil filters, contaminated oil can measures, improper ignition, bearing wear, and high and low crankcase operating temperatures. Such a service provides an excellent control but is of greater value to the mechanic who uses it intelligently as a tool. One value of such analyses is indicated by the experience that many engines operating under optimum conditions have not required repair or an oil change in more than two years when dependence has been placed on service records and oil analyses. However, of more value are the number of engines which have been discovered with serious faults which undoubtedly would have broken down had dependence been placed only on a cursory inspection and service. Oil analyses may also be applied to gear cases to determine oil contamination and wear of bearing surfaces.

In spite of proper application of gas engines, problem wells and conditions will invariably be encountered, one of the most serious of which is temperature variation in the crankcase, leading to condensation and contamination of the lubricant. This condition is often found where equipment is subject to climatic variation, and several devices have been developed to assure a more uniform temperature.

Radiator Shutters

Radiator shutters control the supply of air to the radiator and are usually operated by a vacuum cylinder

through a thermostatic relay mounted between the engine head and radiator. They are quite effective in maintaining a uniform temperature around an engine which is properly housed.

Thermally Controlled Fans

Thermally controlled fans have found considerable application. One type depends on thermal power to vary the pitch of the fan blades in accordance with the temperature. Thermostatic materials confined in a cup act directly on a piston to create the power to control the blades, and no relay or outside source of power is necessary. The fan pitch may vary from zero to thirty-five degrees, and in addition to the temperature control afforded, fan horsepower may be reduced at times with some saving in fuel. Another type is essentially an electric clutch. The rotating speed of the fan varies according to the electric current in the field which is thermostatically controlled through a relay. A source of direct current is necessary for this device.

Vapor Phase Cooling

Vapor phase cooling was designed to eliminate hot and cold spots around the cylinder walls. The jacket water is maintained at or near 212 F and heat is withdrawn from the engine by flashing the water into steam at its exit from the engine, condensing it to water in the radiator, and recirculating it at a temperature near boiling.

Jacketed Crankcase

In order to obtain more uniform temperatures, crankcases have occasionally been jacketed to be included in the cooling water system. It is understood that this has been found particularly useful in areas where contamination of lubricating oil from the fuel is experienced.

Since wide spacing and remote locations are conditions usually faced by the oil producer, traveling time and transportation of materials are major factors in any service program. Furthermore, it is recognized that any successful maintenance program must be directed toward both preventive and corrective measures. It is not desirable to spend much time on equipment that is operating properly so the preventive phases should be made as routine and simple as possible. Provision of tool trucks or even small traveling shops especially designed for the purpose will simplify the routine portion of the work, and adequate and properly arranged tools and repair parts on the job may avoid long trips to find parts.

Haphazard installations of special devices on all pumping units would not be sound, nor would the inauguration of a preventive maintenance program without both consideration of the conditions involved and the benefits to be gained. The cost of inspection and preventive maintenance must be balanced with the cost of downtime and repairs avoided, and each area must be properly evaluated. It has been demonstrated that even in fields where complex conditions exist and mutiple sizes and types of units are used, pumping service of 40 to 60 wells per man is within reason. Also a preventive maintenance program under the same conditions can be carried out at the rate of 50 units per man with 20 per cent of his time allowed for corrective measures and emergency repairs. It is emphasized that any program should be directed toward corrective measures; repairing a failure is usually more expensive than correcting a fault. Preventive maintenance can be made routine whereas failures are unpredictable. and if primary work is routine more attention can be directed to the corrective measures which in the end will assure the producer of a steady, economical operation without costly failure.

* * *

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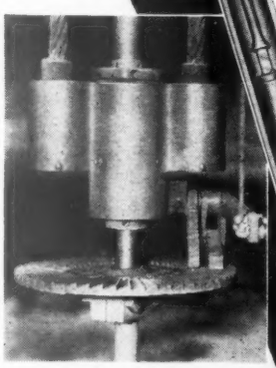
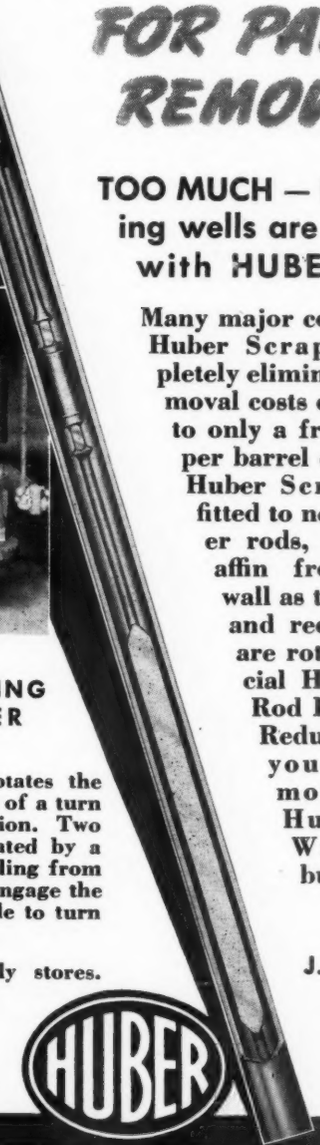


HUBER ROTATING ROD HANGER

This rod hanger rotates the rod string a fraction of a turn on each reciprocation. Two ratchet levers, operated by a flexible cable extending from the walking beam, engage the teeth in the turntable to turn the rod string.

Sold through supply stores.



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The Place of the Engineer in the Drilling Industry*

GEORGE P. LIVERMORE†

My subject "The Place of the Engineer in the Drilling Industry" was more or less picked for me, but I am glad they did not specify what kind of an engineer. I realize a great many of you in this meeting today are petroleum engineers and there may also be some mechanical engineers, and it is natural for you to assume that there is a place for you in this industry, but in all probablity the majority of you will enter the oil industry through the production industry and not through the drilling industry. However, should you consider the drilling industry, one of the first things that you will think of would be "What kind of an industry is this?"

This year it is estimated that the oil industry will spend two billion 935 million 846 thousand dollars[1] for the drilling and producing of oil. In the United States today we are producing an average of 5,500,000 bbl of oil per day. This year the production department, in order to produce the oil, will spend $620,000,000. For the drilling of new wells in proven fields and for wildcat and exploratory wells the drilling industry will spend 2⅓ billion dollars. This means that of all of the money spent by oil companies for the drilling, development and producing of oil this year, 37½ per cent wil be spent in the production department and 62½ per cent will be spent in the drilling department. There will be drilled 136,000,000 ft of new hole with an average cost per foot of $21.10. This cost being divided into wildcat costs of $28.35 per ft of hole drilled and a development expenditure for producing wells of $11.90 per ft of hole drilled.

On December 1 of this year there were approximately 3600 drilling rigs in operation in the U. S. Of this number 2410 were rotary drilling rigs and the balance of 1200 were cable tool rigs. It is estimated that we will drill over 40,000 wells this year. Of all these wells drilled in the United States, 82 per cent are drilled by independent drilling contractors, and 18 per cent are drilled by company owned tools. Another thing that you might keep in mind in analyzing the importance of this industry is that for every 1000 bbl of oil produced, we of the drilling industry must drill 64 ft of hole if we are to maintain our current production. With the amount of money being spent, and the size of this industry, it is amazing to note the scarcity of engineers employed. We undoubtedly have the questionable distinction of being the largest mechanical industry in our modern economy employing the fewest number of engineers.

It might be appropriate at this point to set forth some of the educational requirements of an engineer planning to go into the drilling industry. He should, of course, have a thorough grounding in the fundamentals of engineering which include mathematics, physics, mechanics, hydraulics, therma-dynamics, chemistry, English, etc. In addition to these fundamental courses that are necessary to any engineer, a man preparing himself for work in this industry should, in addition, have specialized courses directed primarily at the problems to be encountered in the technology of the operations of the drilling industry. Such specialized course should include sufficient geology to make him conversant with the work of the geologist on the well. It should include sufficient reservoir engineering to permit him to understand the problems of the reservoir engineer and to prepare him to properly and intelligently handle completion problems and understand the importance of early information obtained at the time of completion of the well. He should have sufficient work in production engineering to permit him to be conversant with, and intelligently handle, any problem related to the equipping of the well after completion. He should have a firm grounding in mechanical engineering courses relating to power generating and transmission equipment, for a drilling rig is above all things a power plant of some complexity.

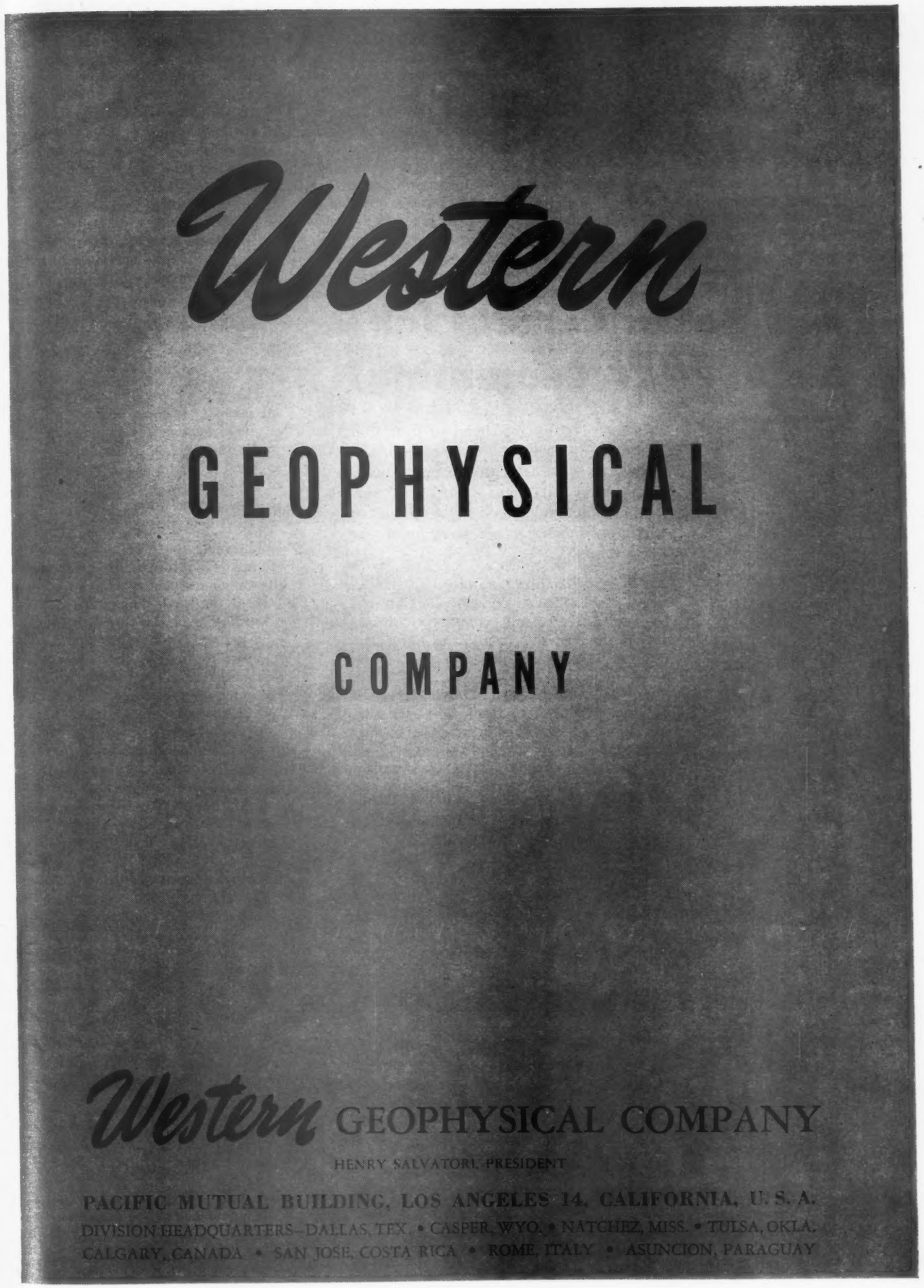
It would seem in order now to point out that the universities cannot, and we of the drilling industry do not expect them to, supply us with finished engineers. In this respect the drilling industry is no different from any other industry employing engineers, and we realize that our industries must share the burden of the universities in training a man to the level on which he can correctly and justifiably be classed as an engineer. We realize that there are two phases to the education of a drilling engineer. One being the technical part of his education; and the universities are equipped to administer that portion. However, upon graduation, he is only half of an engineer, and generally totally lacks the practical and the application phases of his education. Therefore, upon graduation we should be prepared to take over that part of the education of the engineer and supply him with the vast and detailed practical experience of our total operations. This experience and training should begin on the roughneck level and go through every phase and operation encountered in the field. It is only through such broad experience that the drilling engineer in training will acquire the detailed knowledge of our operations that will lead to the development of his judgment and so-called common horse-sense, that are so necessary to his development and effectiveness in the ultimate supervision of our operations.

When the drilling engineer in training has become familiar with and mastered every operation encountered on the roughneck level, when he has *earned* the respect of the other men on the crew, and gained their cooperation, he is then ready to be introduced to the operation of the rig. With a little such transitional training he is then ready for the job of driller. This will be his first supervisory job and if he is to be successful in this position, the rest of the crew must respect his judgment and abilities and he will only have that respect if he has earned it in the lower grades of work.

When the drilling engineer in training has had enough experience in the position of driller to justify his further advancement, his basic field training period will have been completed, and he will be ready to advance to either the position of field engineer or to the position of toolpusher. If he should at this point choose to go the toolpusher route, he will advance in that phase of the drilling operation having primarily to do with the actual drilling of the wells. On the other hand, if the drilling engineer in training chooses

*Excerpts from the paper presented at the Joint Meeting of the Texas Sections, American Institute of Mining & Metallurgical Engineers, University of Texas, Austin, December 16-17, 1948.

†George P. Livermore, Inc., Lubbock, Texas.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to go from the drilling job into the engineering field, his position as field engineer would entail the duties and responsibilities involving the technical aspects of the drilling operations.

If the field engineer develops properly and demonstrates his ability to handle all of these duties and more, he would then be in line for promotion to the position of drilling superintendent. At this level his course of advancement would converge upon that of the engineer in training who had chosen the toolpusher route, as that man would also be in line for promotion to the position of drilling superintendent. In either event, the position of drilling superintendent would ultimately be filled by a man with an engineering training and common experience up to and through the level of driller, but with slightly different experience between the position of driller and drilling superintendent.

This position of drilling superintendent would be in many respects similar to the position of chief operations engineer as found in many other industries. It would entail all of the duties and responsibilities now being carried by the drilling superintendent and having to do with the coordination and operation of the physical aspects of the drilling operations. This logistic control would go down from the drilling superintendent to the toolpushers and to the drillers. In addition to these now normal duties of the drilling superintendent, the position now under discussion would also include the duties of chief engineer and technical director and coordinator of all matters of an engineering nature. This engineering direction and control would go down from the drilling superintendent to the field engineers. In addition to the engineering executive control going downward, it would be the further duty and responsibility of this position to receive and to correlate information and data on field operations as gathered by the field engineers. Upon attaining the position of drilling superintendent, the drilling engineer would have his first executive position.

There is probably no phase of the oil industry where the need of good engineering exceeds that of the drilling industry. Also there is no branch of the oil business where the results of engineering, or the lack of results, will be shown more quickly than in the drilling industry.

The fact that there is a demand for engineers in this field is evident at the present time by the activities of several junior colleges in the Mid-Continent area and in California who have set up a two-year course in drilling engineering. In my opinion this is an all too feeble attempt and falls far short of the need. These courses are little more than trade school courses and fail to give the student the broad fundamental training that is an absolute essential to the man going into this work. Various business analysts have estimated the mortality rate for drilling contracting firms to be 97 per cent. With these facts in mind it can be of little wonder that drilling contractors are reluctant to turn their engineering over to a man with anything less than the best in undergraduate engineering training and post-graduate field training, when a wrong decision can cost the contractor a few hundred thousand dollars or put him out of business. On the other hand, if the drilling industry had its proper complement of well qualified engineers we might be able to reduce this mortality rate appreciably.

I hope that I have not discouraged you too much about the life and opportunities of an engineer in the drilling business because we certainly do need you, but if we have you, you must be good, because if you make too many mistakes both you and your boss will in all probability be looking for another job. ★ ★ ★

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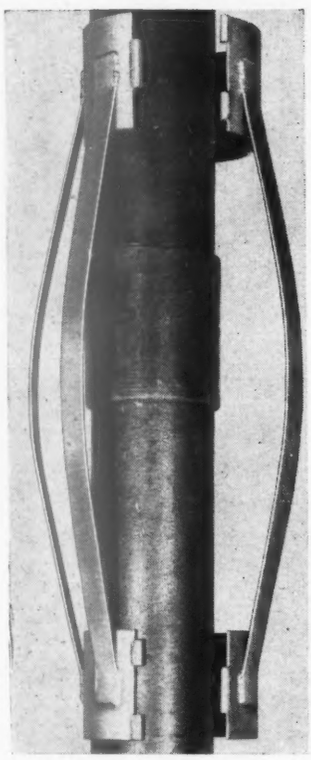

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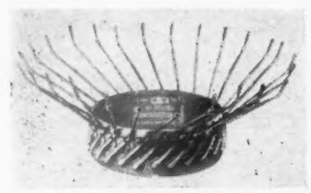

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Various Refinery Applications of Houdriflow Catalytic Cracking*

G. F. HORNADAY†, H. D. NOLL†, C. C. PEAVY†, W. WEINRICH†

Abstract

The refinery studies are made on the basis of processing 10,000 BPCD of East Texas crude. The variable cases are as follows:

1. Visbreaking and thermal cracking the 40 per cent East Texas residuum.

2. Tar separating the 40 per cent East Texas residuum, and visbreaking the 15 per cent East Texas bottoms in an integral visbreaker, once-through catalytically cracking the tar separator overhead and visbreaker overhead plus the excess light virgin gas oil. The catalytic cycle stock is thermally cracked.

3. Same as (2) except recycle catalytic cracking without thermal cracking the cycle stock.

4. Coking the 15 per cent East Texas bottoms plus catalytically cracking the tar separator overhead, coker gas oil and excess virgin gas oil. Thermally cracking the catalytic cycle stock.

5. Same as (4) except recycle catalytic cracking without thermal cracking of the cycle stock.

6. Vacuum distilling the residuum and catalytically cracking the vacuum distillate plus excess virgin gas oil and thermally cracking cycle stock.

In all cases the 250 F end point straight-run gasoline is used directly in the motor gasoline, the 250 F-400 F straight-run naphtha is reformed and the C^3 and C^4 fractions are charged to a catalytic polymerization unit.

THE petroleum industry is now confronted with a difficult problem in regard to the production of distillate and residual fuel. The supply of these fuels has exceeded demand. The price of residual fuel has dropped drastically within the past few months and distillate fuel prices are decreasing also. In addition the stocks of these fuels in storage have risen sharply and crude runs to the stills have been reduced in some refineries for the first time since the early part of 1946. A survey of the stocks and prices for January, 1948 and 1949, indicates over 60 per cent increase in residual and distillate fuel stocks in storage and a decrease in price of from 10 to 30 per cent.

Comparative oil stocks and prices for 1948 and 1949.

	In storage, million bbl			Price (Gulf Coast)	
Stock	1/15/49	1/17/48	% Increase	1/1/49	1/1/48
Crude	241	220	9.8	2.65$/B.	2.65$/B.
Gasoline	109	99	10.6	11.0–13.5c/Gal.	12.9–13.5c/Gal.
Residual fuel	85.6	51.6	66.0	2.05–2.08$/B.	2.56–3.50$/B.
Distillate fuel	93.1	57.5	62.0	9.0–9.5c/Gal.	9.0–11.5c/Gal.

API Refinery Report and Oil and Gas Journa

The best available tool for bringing the production of fuel oil into balance is catalytic cracking. Another factor contributing to an increase in cracking operations is the inrease in octane rating. It is not unreasonable to expect material increases in octane numbers in the near future, since engine designers are experimenting with higher compression engines than those currently in production.

The sharp drop in the price of fuel oils makes it expedient at this time to re-examine the economics of refinery cracking operations.

The purpose of this paper is to review the economics of catalytic cracking as applied to several methods of refinery operation. The major difference in the various operating schemes centers in the methods of preparing the feed stock for catalytic cracking.

For the purpose of this study four typical methods of refinery operation have been selected. These include thermal cracking, alone, and combinations of catalytic cracking with vacuum-distillation, visbreaking, and delayed coking of the reduced crude.

The processing schemes covered are listed below and simplified flow diagrams for these schemes are given in Fig. 1 and 2:

1. *Thermal.* This processing scheme consists of conventional two-coil thermally cracking the 40 per cent volume East Texas residuum to an ultimate yield of motor gasoline.

2. *Vacuum-Distillation.* The 40 per cent volume East Texas residuum is vacuum-distilled to produce an 8.0 per cent volume asphalt. The vacuum gas oil plus the excess light virgin gas oil is catalytically cracked, and the catalytic cycle stock remaining after blending the tar bottoms to No. 6 fuel oil specification is thermally cracked.

3. *Visbreaking.* The 40 per cent volume East Texas residuum is charged to a flash tower and the resulting bottoms is visbroken and returned to the common flash tower. The flash tower overhead stock plus excess virgin gas oil are catalytically cracked and the catalytic cycle stock remaining after blending the tar bottoms to No. 6 fuel oil specification is thermally cracked.

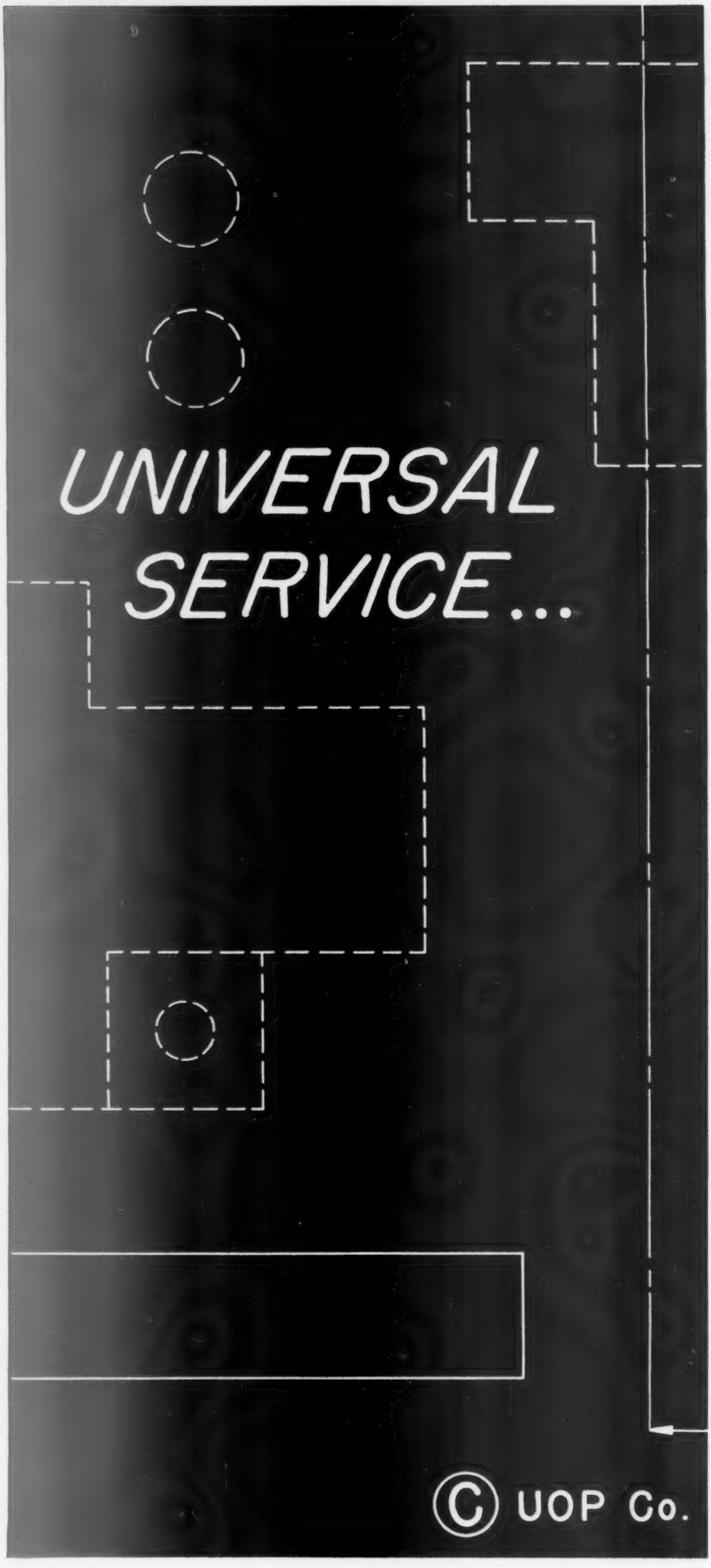
4. *Coking.* The 40 per cent volume East Texas residuum is flash-distilled to obtain an overhead fraction and the resulting bottoms is coked. The combined flash tower overhead and total coker distillate plus excess light virgin gas oil are catalytically cracked and the catalytic cycle stock is thermally cracked.

In order to further this study two additional processing schemes were calculated to show the effect of recycle catalytic cracking instead of thermally cracking the cycle stock. The two additional situations are alternates for the visbreaking and coking processing schemes and are designated 3A and 4A.

The basic yield data on which this

*Presented before the Thirty-seventh Annual Meeting of the Western Petroleum Refiners Association, San Antonio, Texas, March 28-30, 1949.

†Houdry Process Corporation, Philadelphia, Pennsylvania.



Deep Rock Modernizes Cushing Refinery

By W. J. Carthaus

Vice President in charge of Manufacturing and Research, Deep Rock Oil Corporation

THE installation of a 5,000 barrel fluid catalytic cracking unit at our Cushing, Okla., refinery will be one of the major steps in a program of modernization and expansion which is designed principally to produce superior quality products and more efficiently. Doing this will enable us to satisfy the requirements of any internal combustion engine likely to be produced commercially for some time.

W. J. Carthaus

Deep Rock pioneered in thermal cracking in the Mid-Continent field more than a quarter century ago with one of the earliest installations of a thermal unit designed by Universal Oil Products Company. The new fluid catalytic cracking unit, which will include a gas concentration system and feed preparation facilities, is being designed by UOP.

Single Column Unit

The cat cracker will follow UOP's improved design with reactor and regenerator incorporated in a single column. It will produce catalytically cracked gasoline, domestic burner oil and cycle stock. In addition, crude facilities will be increased through the installation of a crude distillation unit.

The gas concentration system will depropanize and debutanize the catalytically cracked gasoline, and at the same time prepare feed stock for the catalytic polymerization unit. The feed preparation system for the cat cracker will consist of a combination of vis-breaking and vacuum distillation designed to give maximum flexibility.

It is interesting to note that the installation of the cat cracker will not mean the retirement of the thermal cracking plant from service, although its operation will be modified.

The present thermal cracker is a two-coil unit with rated capacity of 5,000 barrels per day. Under the new set-up the heavy oil heater will be converted to vis-breaking service as part of the cracker's feed preparation system and the light oil heater will be changed for single coil operation to crack the heavy cycle stock from the cat cracker if that should prove desirable, as well as any other available cracking stock.

To Double Poly Unit

We have at the present time, a catalytic polymerization unit which processes the gas from the thermal cracker. It

(Advertisement)

will be necessary to practically double the capacity of the poly unit, now producing about 160 barrels per day of 82 octane (Motor Method) polymer gasoline, in order to take care of the additional gas produced in the cat cracking operation. When increasing the size of this poly unit, additional provision will be made for the recovery of propane and butane from the poly plant effluent, to be marketed as LPG. The LPG facilities will utilize, in addition to two new vessels, two existing flash chambers which were formerly part of the original small thermal cracker.

Expansion of our crude capacity and the installation of the cat cracker, necessitates considerable change throughout the plant. All main transfer lines will be replaced with lines of greater capacity and 200,000 barrels of additional tankage must be constructed. To maintain a constant check on our increased operations, and to assure uniform high quality, we plan to virtually double the size of our control laboratories.

More steam is another necessity and our plans call for the installation of an additional boiler to deliver 40,000 pounds of steam per hour. We are also confronted with a great increase in our water requirements. Our boiler feed water, presently amounting to 350,000 gallons per day, will be raised to about 500,000 gallons, all drawn from the Cushing municipal system.

Complete cooperation on the part of the city has been pledged and we are assured of the additional 150,000 gallons we will need. Our process cooling water is drawn from the Cimarron River and it will be necessary to enlarge our lines and pumping facilities to handle an increased volume of water.

Enlarged Modern Office Building

Better working conditions for our refinery office staff are being provided and the existing building is being greatly enlarged and completely modernized. Plans call for the installation of the latest type of air conditioning throughout the building.

New Research Laboratory

One part of our expansion program which we consider of major importance is the construction of an air conditioned building to house a research and development laboratory. This is to be entirely independent of the control laboratory so that research men will not be diverted from their work for plant trouble shooting or to solve purely operational problems. This research and development service will be divided into four parts including research, technical service to customers, new product development and engine laboratory research on fuels and lubricants.

The Cushing refinery is located on the Great Lakes pipeline and our gasoline moves to market in that way. Many of our special products such as technical naphthas and lubricating oils, however, must be transported by rail. To facilitate the loading of such products we are replacing our present loading rack with a more efficient installation.

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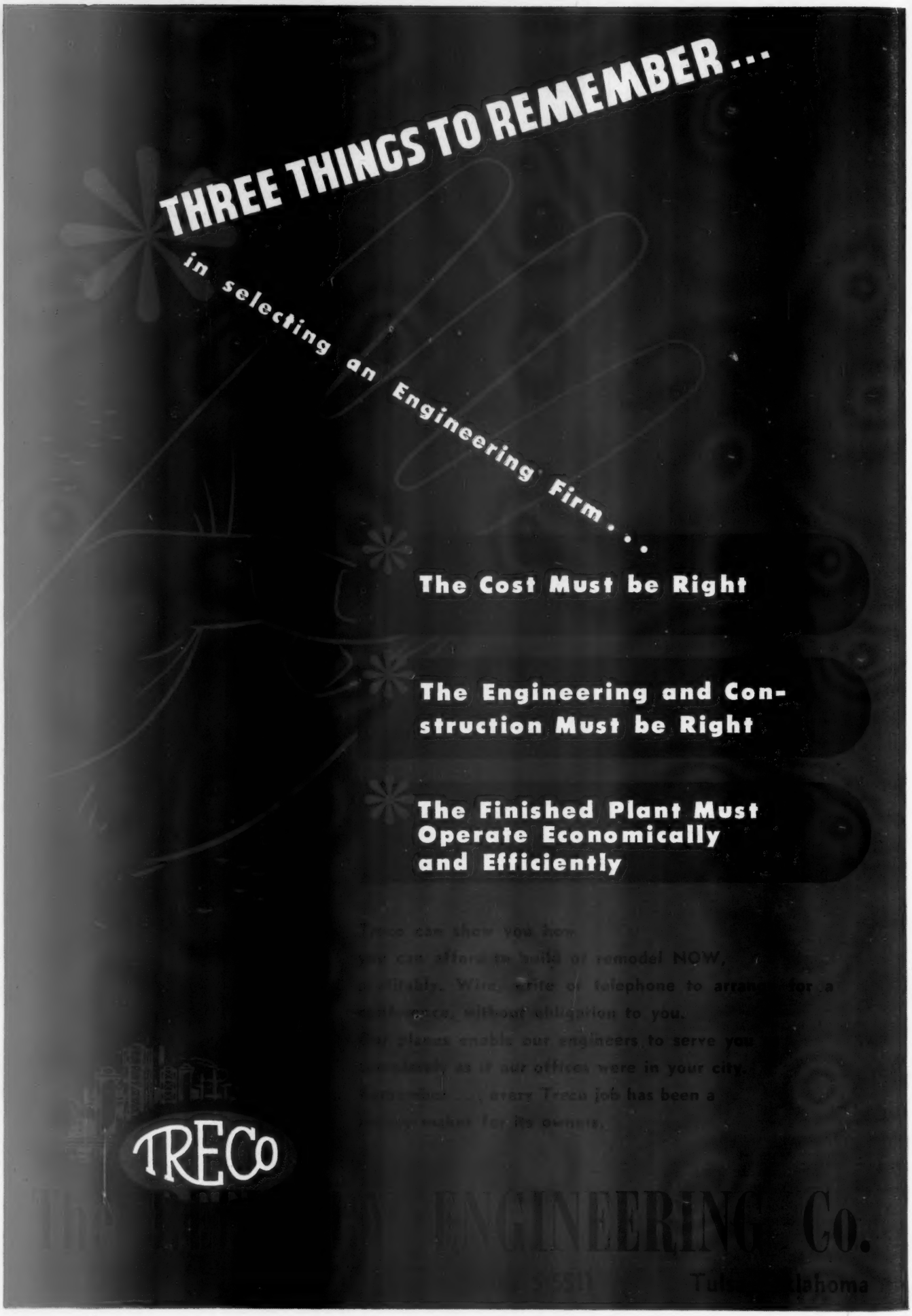
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The Cost Must be Right
The Engineering and Construction Must be Right
The Finished Plant Must Operate Economically and Efficiently
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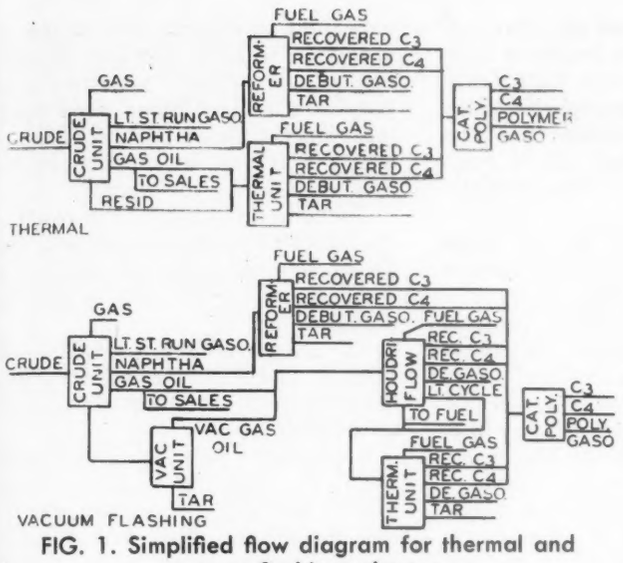

FIG. 1. Simplified flow diagram for thermal and vacuum flashing schemes.

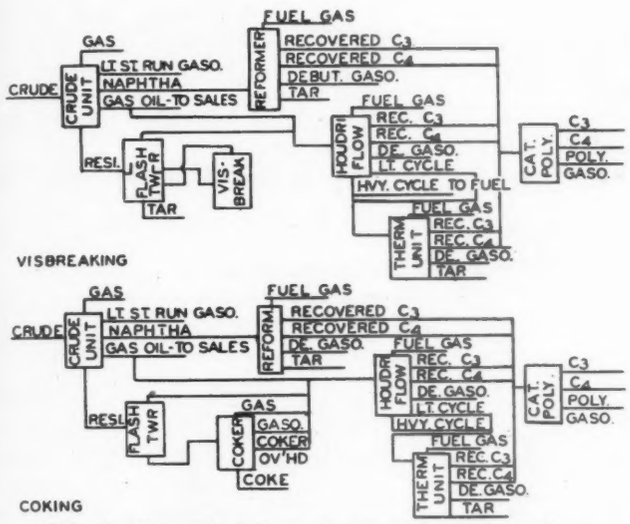

FIG. 2. Simplified flow diagram for visbreaking and coking schemes.

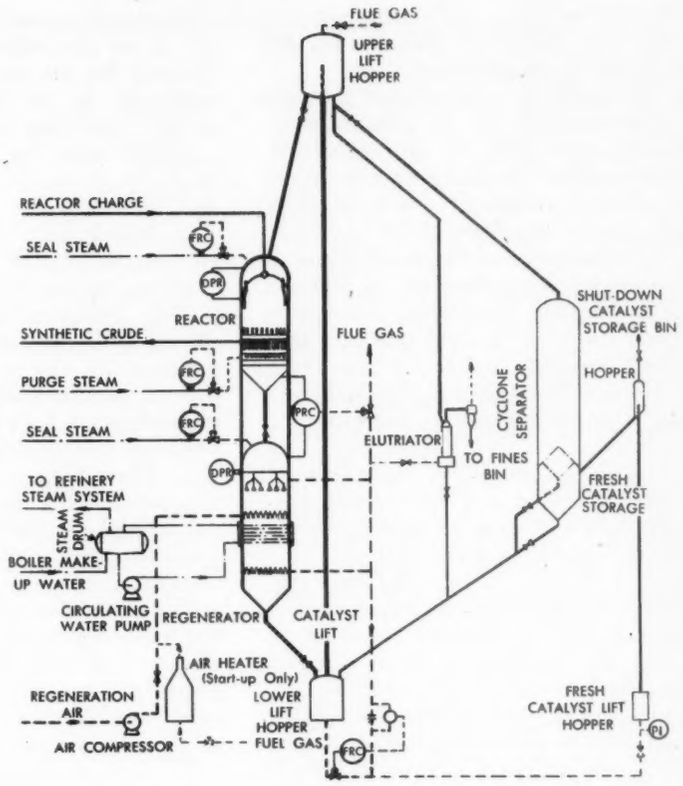

FIG. 3. Flow diagram Houdriflow catalytic cracking process.

survey is based were obtained during an extensive pilot plant program by the Houdry Laboratories, to determine the effect of method of stock preparation on the catalytic cracking characteristics of the resulting stocks. During this laboratory program stocks were prepared from East Texas reduced crude by coking, vacuum-distillation, and by visbreaking to various severity levels. These stocks were cracked in a pilot catalytic cracking unit. Gasoline and fuel blends were prepared and tested.

In the economic study, the crude charge is assumed to be 10,000 B.P.C.D. of East Texas crude. The crude is distilled to obtain a 250 F E.P. straight run gasoline, a 250-400 F straight run naphtha, a light gas oil for diesel or No. 2 fuel, and a 40 per cent volume residuum. The 250 F E.P. straight run gasoline is used directly in the final motor gasoline blend. The 250-400 F naphtha is thermally reformed to obtain a 70 octane distillate. It was assumed that 1000 B.P.C.D. of light gas oil goes to sales, and the remaining 960 B.P.C.D. is available as catalytic cracking charge stock. The C_3 and C_4 fractions from the thermal and catalytic operations are charged to a catalytic polymerization unit to produce a polymer for use in the motor gasoline blend.

In the economic comparisons the following typical Gulf Coast price structure and utility values were assumed to be representative of the prices existing at this time. It is recommended that individual refiners substitute their own price structure in order to determine their particular economics.

Stock	Price
East Texas Crude, bbl	$2.95
Motor Gasoline, gal	0.115
Diesel Fuel, gal	0.085
No. 2 Fuel, gal	0.085
No. 6 Fuel, bbl	1.50
Butanes, gal (Fuel Value)	0.025
Fuel Gas, MM Btu	0.25
Steam, M lb	0.35
Power, KWH	0.008
Water (Cooling), M gal	0.005
Water (Treated), M gal	0.15
Clay Catalyst, lb	0.05

The overall maintenance cost for the processing equipment was assumed at 4.0 per cent of the investment. The taxes, interest, and insurance costs were estimated at 5.0 per cent of the investment. The royalty rates were assumed to be 5 cents per bbl of fresh feed for catalytic cracking, 3 cents per bbl of fresh feed for

thermal cracking and reforming, and 0.5 cents per gal of polymer for the catalytic polymerization.

It should be pointed out that the investments are for the primary processing equipment. No storage of offsite auxiliary facilities have been included. Consequently, net earnings are purely comparative.

The features of the main types of processing equipment are as follows:

1. *Thermal Cracking.* A conventional two-coil thermal cracking unit was assumed to handle the East Texas residuum with provision for visbreaking the residuum and cracking the light oil.

2. *Vacuum-Flashing.* The reduced crude is flashed in a conventional vacuum tower and the vacuum gas oil is charged to the catalytic unit.

3. *Visbreaking.* In order to minimize the investment by eliminating a flash tower, an integral type flow is used. The reduced crude is charged to a flash tower and the resulting bottoms is charged to a visbreaker heater and then to the common flash tower. The combined vapor from the flash tower is charged to the catalytic unit.

4. *Coking.* A drum type delayed coking unit is used and the charge is the 15 per cent volume residuum from flashing the 40 per cent East Texas residuum in an atmospheric flash tower. The coker overhead products combine with the flash tower overhead for processing in the catalytic equipment.

5. *Houdriflow.* In all of these studies the new Houdriflow catalytic cracking process is used.

This catalytic cracking process, shown in Fig. 3, retains the desirable features of the conventional TCC process and in addition a number of improvements have been made which result in greater flexibility and lower cost. These improvements include a new method for moving catalyst, the use of higher catalyst to oil ratios, a simplified kiln, and a more compact physical arrangement of the vessels.

The use of flue gas for lifting catalyst is more attractive than the bucket elevators in that it is cheaper, decreases the number of mechanical devices, and permits a wider range of catalyst circulation rates.

The use of a higher catalyst to oil ratio permits considerable flexibility in operation in that liquid, partially vaporized, or vaporized stocks may be processed without difficulty. The use of liquid or partially vaporized stock simplifies the feed preparation equipment since a major portion of the reaction heat can be supplied by the catalyst entering the reactor.

The simplified kiln is the result of the increased catalyst circulation. One or two burning zones are sufficient as compared to 7 to 10 zones in previous designs.

The reactor is superimposed on the kiln in order to minimize catalyst handling and to reduce the ground area requirement.

Regenerated pelleted or bead catalyst in the upper lift hopper flows by gravity through the reactor seal leg into the reactor. The catalyst passes downward through the reaction zone, through vapor-disengaging and steam-purging sections in the bottom of the reactor. It then goes by way of the seal leg into the distributing head of the kiln. The spent catalyst flows into the kiln proper through a distributor, designed to insure uniform distribution, and continues downward through the regenerator.

Leaving the bottom of the kiln, the

TABLE 1. Summary of economics—processing—10,000 BPCD East Texas crude.

Scheme number		1		2		3		4		3A		4A	
Processing		Thermal		Vac. Dist. Once thru Cat. Crack.		Visbreaking Once thru Cat. Crack.		Coking Once thru Cat. Crack.		Visbreaking Recycle Cat. Crack.		Coking Recycle Cat. Crack.	
Revenue	$/bbl.	BPCD	$/day	BPCD	$/day	BPCD	$/day	BPCD	$/day	BPCD	$/day	BPCD	$/day
10lb RVP motor gasoline	$4.830	6,126	29,589	6,694	32,332	6,797	32,830	7,370	35,597	6,745	32,578	7,120	34,390
Diesel fuel	3.570	1,000	3,570	1,000	3,570	1,000	3,570	1,000	3,570	1,000	3,570	1,000	3,570
No. 2 fuel	3.570	....	....	....	....	....	....	....	....	505	1,803	629	2,246
No. 6 fuel	1.50	2,378	3,567	1,781	2,672	1,623	2,435	826	1,239	1,024	1,536	243	365
Dry gas (F.O.E.)	1.50	739	1,109	744	1,116	794	1,191	858	1,287	753	1,130	794	1,191
Excess butane (as fuel)	1.05	....	....	43	45	65	68	80	84	124	130	130	136
Coke	5.00$/T.	....	....	....	....	....	....	....	220	....	....	....	220
Total revenue			37,835		39,735		40,094		41,997		40,747		42,118
Operating Costs													
Crude	2.95$/B.	10,000	29,500	10,000	29,500	10,000	29,500	10,000	29,500	10,000	29,500	10,000	29,500
Crude distillation		10,000	772	10,000	772	10,000	772	10,000	772	10,000	772	10,000	772
Houdriflow cracking		....	....	4,167	703	4,272	812	4,767	815	8,544	1,063	9,534	1,093
Gas plant		....	238	....	592	....	605	....	654	....	629	....	679
Thermal cracking		4,960	1,089	1,552	489	1,614	500	2,083	585	....	....	....	....
Thermal reforming		1,990	453	1,990	453	1,990	453	1,990	453	1,990	453	1,990	453
Vacuum distillation		....	....	4,000	355	....	....	....	....	....	....	....	....
Coking		....	....	....	....	....	....	1,497	427	....	....	1,497	427
Catalytic polymerization		261	226	358	256	373	261	422	276	373	261	407	272
TEL to 80 O.N. (F-2)(1,000 cc's)	0.22c/cc	437	962	210	464	228	502	337	742	147	324	203	447
Gasoline inhibitor		6,241	6	6,694	7	6,797	7	7,370	7	6,745	7	7,120	7
Taxes, int., ins.		....	401	....	647	....	589	....	695	....	586	....	678
Houdriflow royalty	5.0c/B.	....	....	4,157	208	4,272	214	4,767	238	4,272	214	4,767	238
Thermal royalty	3.0c/B.	6,950	209	3,542	106	3,604	108	4,073	122	1,990	60	1,990	60
Cat. poly royalty	21.0c/B.	261	55	358	75	373	78	422	89	373	78	407	85
Total operating costs			$33,911		$34,627		$34,401		$35,375		$33,947		$34,711
Earnings, $/CD			3,924		5,108		5,693		6,622		6,800		7,407
Payout time, years			2.04		2.53		2.07		2.10		1.72		1.83
TEL to 78 on (F-2)(1,000 cc's)		283	$ 623	104	$ 229	114	$ 251	186	$ 409	65	$ 143	96	$ 211
Earnings, $/CD			4,263		5,343		5,944		6,955		6,981		7,643
Payout time, years			1.89		2.42		1.98		2.00		1.68		1.77
TEL to 82 on (F-2)(1,000 cc's)		669	$ 1,472	388	$ 854	399	$ 878	557	$ 1,226	306	$ 673	389	$ 855
Earnings, $/CD			3,414		4,718		5,317		6,138		6,451		6,999
Payout times, years			2.35		2.74		2.22		2.27		1.82		1.94
Investments (Process equipment only)													
Crude distillation			$ 700,000		$700,000		$700,000		$700,000		$700,000		$700,000
Houdriflow catalytic & feed prep.					1,505,000		1,550,000		1,600,000		1,900,000		1,960,000
Vacuum unit					500,000								
Gas plant			680,000		775,000		800,000		840,000		825,000		850,000
Thermal crack. and reforming			1,180,000		800,000		800,000		880,000		400,000		400,000
Catalytic polymerization and treating			370,000		440,000		450,000		485,000		450,000		470,000
Coker									570,000				570,000
Total			$2,930,000		$ 4,720,000		$4,300,000		$5,075,000		$4,275,000		$4,950,000

catalyst flows by gravity through a seal leg into the lower lift hopper from which point it is transported by means of flue gas from the kiln through a vertical lift pipe into the upper lift hopper. As in the conventional TCC process, a small stream of catalyst is continuously bypassed to the elutriator where "fines" are removed by air classification to maintain the average particle size of the catalyst in the system at the desired value.

The oil charge enters the reactor through an injection nozzle, located centrally in the top of the reaction zone and inside the annular curtain of flowing catalyst. By means of the injection nozzle the mixed-phase feed is atomized and directed onto the annular curtain of hot catalyst which immediately completes the vaporization of the charge and brings the temperature of the vapor-catalyst mixture to the desired level for reaction. The hydrocarbon vapors then pass downward concurently with the catalyst through a solid-bed reaction zone.

The cracked vapors of synthetic crude leave the reaction zone via a catalyst-vapor disengager in the lower part of the reactor and flow to a conventional fractionation and recovery plant.

A small flow of steam into the head of the reactor, automatically regulated by a recording flow controller, maintains a seal at the top of the reactor to prevent the escape of hydrocarbon vapors up the seal leg and, similarly, the purge steam in the bottom of the reactor precludes the possibility of escape of cracked vapors through seal leg into the regenerator.

Air for regeneration of the spent catalyst, supplied by a blower at about 10 psig, by-passes the air heater which is used for start up only, and enters the kiln through a channel-type distributor. Flue gases from the upper burning zone disengage above the catalyst distributor, leave the top of the regenerator, and enter the main flue gas duct. Flue gases from the lower burning zone leave the bottom of the regenerator by way of a channel type collector and also enter the main flue gas duct. A bank of cooling coils in the kiln removes regeneration heat as steam to maintain the desired catalyst temperatures.

The flue gas for the catalyst lift enters the lower lift hopper through a flow controller, engages and carries the catalyst up the lift pipe to the upper lift hopper, and from this point is vented to the atmosphere.

A summary of the relative advantages of the various processing schemes when producing a gasoline having an 80 F-2 octane rating as follows:

Scheme No.	Processing	Investment	Payout period Years	Earnings $/CD	No. 6 fuel produced % on crude	c.c. T.E.L. to 80 O.N. Motor
1	Thermal	$2,900,000	2.04	3924	23.78	1.7
2	Vacuum-Distillation	4,720,000	2.53	5108	17.81	0.75
3	Visbreaking	4,300,000	2.07	5693	16.23	0.80
4	Coking	5,075,000	2.10	6622	8.26	1.09
3A	Visbreaking—Recycle Cat. Cracking	4,275,000	1.72	6800	10.24	0.52
4A	Coking—Recycle Cat Cracking.	4,950,000	1.83	7407	2.43	0.68

The summary indicates that at the present gasoline prices and provided the refiner has a market for coke, the delayed-coking process is a very attractive method for perparing catalytic cracking feed stocks. Although the coking scheme results in the largest investment, the pay-out time compares very favorably with the other processes, and the earnings per day are appreciably higher than for the other processes. Visbreaking compares favorably with the coking process in that it has a lower investment, slightly lower pay-out time, but produces lower earnings. Recycle catalytic cracking of the cycle stocks (Schemes 3A and 4A) indicates reduced pay-out times and higher earnings over once-through catalytic cracking, followed by thermal cracking of the net cycle stocks after fuel blending. Complete investment, operating costs, and earnings are summarized in Table 1. Basic yield data for the various operations are shown in Tables 2, 3, and 4.

The effect of the price of residual fuel on the pay-out time with once-through catalytic cracking and with recycle cracking is shown in Fig. 4 and 5. Variation in the fuel price produces the greatest effect on the earnings of the processing schemes producing the most residual fuel. The coking scheme is the least affected by the price of fuel. Recycle catalytic crack-

TABLE 2. Thermal reforming yields.

Scheme number	1-6
Charge to unit, BPCD	
250-400F. Naphtha	1960
Yields based on charge, % volume	
Debut. gasoline	73.5
Fuel oil	3.0
Isobutane	1.5
Normal butane	2.3
Butenes	5.4
Propylene	5.1
Dry gas (C_3+lighter), % wt.	15.3
Octane ratings (F-2)	
Charge	46.0
Product	70.0

TABLE 3. Houdriflow catalytic cracking yields.

Scheme numbers	2	3	4	3A	4A
Charge to Unit, BPCD					
Diesel fuel	960	960	960	960	960
Flash tower overhead					
Virgin	....	2504	2504	2504	2504
Visbreaker	....	808	....	808	....
Coker overhead	....	....	1303	....	1303
Vacuum gas oil	3179	....	....	....	....
Recycle	....	....	....	4272	4767
Total	4157	4272	4767	8544	9534
Yields based on fresh charge, % volume					
Debut. motor gasoline	42.0	41.8	43.2	59.0	59.4
Catalytic gas oil	45.8	44.2	43.7	18.2	18.3
Isobutane	5.0	5.1	5.1	7.4	7.1
Normal butane	1.8	1.9	2.0	2.7	2.7
Butenes	4.3	4.3	4.8	5.5	5.6
Propylene	2.6	2.9	3.2	4.3	4.4
Dry gas (C_3+lighter), % wt.	5.9	6.8	6.2	10.7	10.5
Carbon, %wt.	4.6	5.0	5.5	8.4	9.5
Carbon, lb/Hr. (stream day)	2710	3020	3717	5140	6489

TABLE 4. Thermal cracking yields.

Scheme numbers	1	2	3	4
Charge stock, PBCD				
Diesel	960	....	....	....
Reduced crude	4000	....	....	....
Catalytic gas oil	....	1552	1614	2083
Total	4960	1552	1614	2083
Gravity, °API	24.8	28.5	26.9	27.6
Yields—% volume				
Debut. motor gasoline	43.4	47.5	47.7	47.1
Isobutane	1.8	1.4	1.4	1.4
Normal butane	1.4	3.2	3.4	3.3
Butenes	2.6	3.6	3.6	3.6
Propylene	2.1	3.0	3.0	3.0
Fuel oil	46.7	36.5	37.1	36.8
Dry gas (C_3+lighter), % wt	8.3	12.5	12.5	12.5

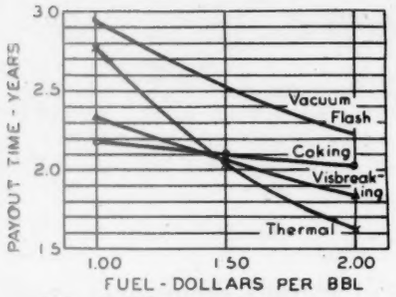

FIG. 4. Effect of fuel price on payout time.
Gasoline 11.5¢ per gal.

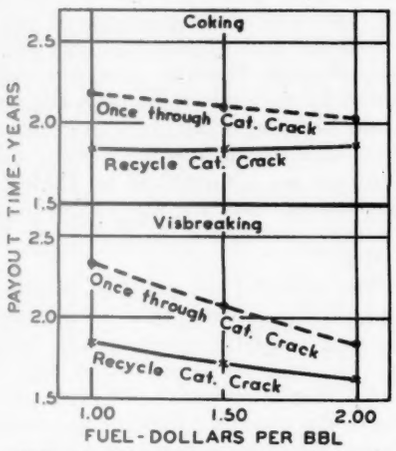

FIG. 5. Comparison once through and recycle catalytic cracking on payout time.

ing minimizes residual fuel when compared to once-through catalytic cracking, followed by thermal cracking of the catalytic cycle stock. The recycle operation is affected less by the price of fuel, and shows considerable advantage over once-through cracking.

As the gasoline price increases, with fuel price remaining constant, the advantage of the coking, vacuum-flashing, and visbreaking over thermal cracking increases. The differential earnings between the various processing schemes are only slightly affected by substantial changes in gasoline price. This is illustrated in Fig. 6 and 7.

The lead requirements for the motor gasoline blends vary appreciably depending on the method of processing. A brief summary of the lead requirements is as follows:

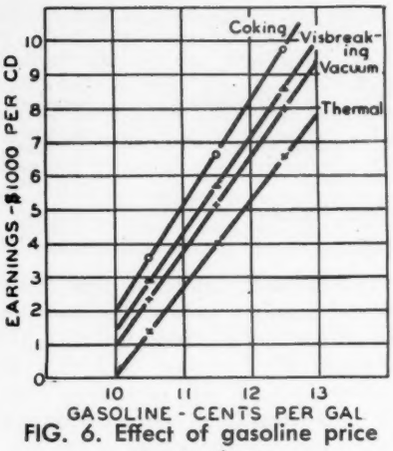

FIG. 6. Effect of gasoline price on earnings.
Basis—Fuel 1.50$ per bbl.

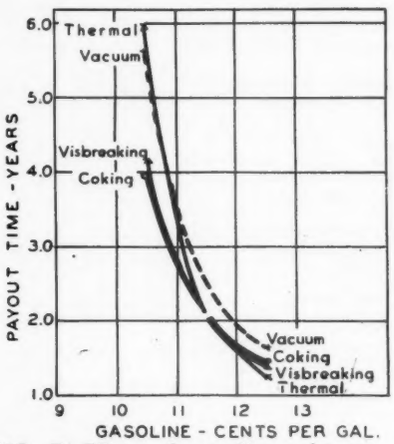

FIG. 7. Effect of gasoline price on payout time.
Fuel 1.50$ per bbl.

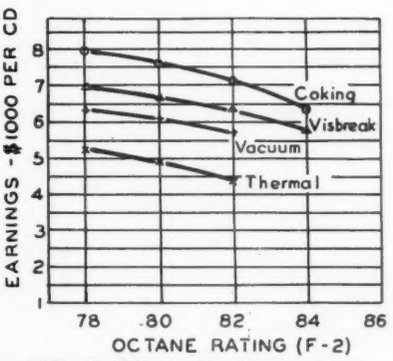

FIG. 8. Effect of octane rating on earnings.
Basis
Fuel 1.50$ per bbl.
Gasoline 11.5¢ per gal.

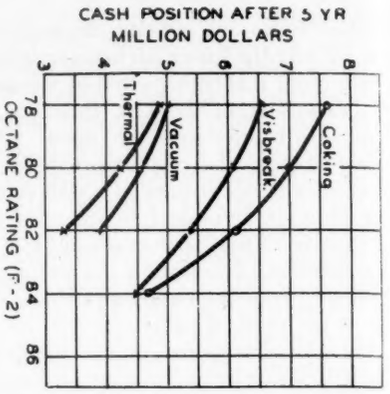

FIG. 9. Effect of octane requirement on cash position after 5 years.
Basis
Fuel 1.50$ per bbl.
Gasoline 11.5¢ per gal.

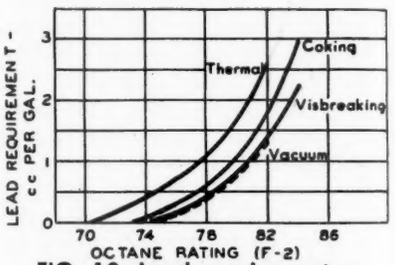

FIG. 10. Lead requirement vs octane rating.

On the basis of this summary it is apparent that as the octane level is increased the advantage of catalytic cracking over thermal cracking increases. The advantage of coking over visbreaking decreases because of the higher lead requirement. The higher lead requirement is the result of the lower octane of the coker gasoline.

If the lead content of the gasoline had been held constant and the octane difference corrected by the amount or severity of naphtha-reforming, the relative advantage of catalytic cracking over thermal cracking would be enhanced.

The influence of the octane rating requirement of the motor gasoline on the economics is shown in Fig. 8 and 9. The lead requirements for the various gasolines are presented in Fig. 10.

The studies as presented in this paper indicate the following conclusions:

1. At the present market conditions, coking or visbreaking are the best methods for preparing catalytic cracking charging stocks.

2. More catalytic cracking capacity appears necessary because of the octane advantage of catalytic over thermal gasolines.

3. To minimize the production of residual fuel, the use of catalytic cracking is advantageous. ★ ★ ★

Scheme No.	Processing	Lead requirement, cc/Gal. 78 O.N.	80 O.N.	82 O.N.	84 O.N.
1	Thermal	1.1	1.7	2.6	....
2	Vacuum-Distillation	0.37	0.75	1.38	2.15
3	Visbreaking	0.4	0.8	1.40	2.2
4	Coking	0.6	1.09	1.8	2.95
3A	Visbreaking—Recycle cat. crack	0.23	0.52	1.08	1.7
4A	Coking—Recycle cat. crack	0.32	0.68	1.30	2.0

Control of Maintenance Costs†

R. S. STEWART* and H. A. GUSTAFSON*

With labor and material costs climbing steadily, refinery managements are directing attention to improving maintenance practices. Accurate and timely cost reports of current methods are essential:

1. As a key to determining need for improvement.

2. As a gage to measure the success of improvements made.

The authors have outlined the procedure their company adopted to insure accurate and current monthly costs. The discussion briefly touches on the functions of an automatic business-machine installation, and necessarily mentions accounting changes found necessary. The body of the paper is devoted to discussing actual maintenance-cost reports. Case histories are cited of typical instances where these reports uncovered excessive maintenance costs, and where they led to better methods and practices.

Because of the versatility of the business-machine installations, labor and material costs are reported simultaneously for:

1. Maintenance of particular refinery units or processes.

2. Maintenance of types of equipment in a particular unit or process.

3. Completed maintenance jobs.

4. Individual jobs at a unit shutdown or turnaround.

5. Maintenance of each pump, motor, compressor, etc.

6. Expenditures of particular appropriations.

Subsidiary reports show:

1. Jobs which "hang fire" more than a month.

2. The craft man-hours required to maintain each refinery unit.

3. The proportion of planned work to emergency jobs.

4. The number of man-hours expended by each craft on shutdown and turnaround jobs.

5. The number of overtime hours each craft expends.

6. Inventory turnover of maintenance material.

The authors have taken examples of each type of report, and have illustrated its use in comparing it with estimated or planned amounts. They have traced the steps where these reports have been applied for the purpose of effecting actual maintenance-cost reductions.

THE petroleum industry is proud of its vigor and resourcefulness. Its history is a record of dynamic growth and expansion. Today the military importance of petroleum products is exceeded only by their importance to American peacetime living. Keeping pace with this dual demand offers a repeated challenge. In accepting this challenge, and in fulfilling its obligations to society, the vision and ingenuity of the oil industry deserves full credit.

Need for Maintenance Research and Analysis

This progressive leadership emphasizes technology in the refining division. *Process* problems are now analyzed in detail in the laboratory and in the field. Technical knowledge and initiative receive a free hand. New refining methods, improved products, and increased refining capacity result. Such research and study will receive further stimulation. Modern research laboratories recently were completed by several major oil companies. Confidence in the value of the scientific approach to refinery *process* problems is firmly established.

Maintenance costs and methods also offer fertile fields for the application of this same vision and ingenuity. Frequently new or improved methods of refinery maintenance are not thoroughly investigated or encouraged. Failure to use adequate and sufficient tools is a frequent fault. Failure to use trained engineers in the maintenance field is a handicap. In short, the progress and development of *maintenance* research and analysis have not kept abreast of the emphasis placed on the process side of refining. We believe the possible rewards fully justify the application of modern industrial engineering principles to refinery-maintenance work.

Benefits From Improved Maintenance

Benefits from improved maintenance are many. The productivity of the worker increases. Shutdowns and turnarounds are shorter and less frequent. Refinery output increases. Repairs last longer. Equipment operates efficiently. By utilizing existing equipment a larger percentage of the time and of capital expenditures for expanded capacity is conserved. These are some of the advantages realized from better maintenance practices. They save money. They reduce the cost of refinery operation. They apply to *small* as well as to *large* refineries.

Program to Improve Maintenance Methods

Recognizing the potentialities of better maintenance methods in ultimately reducing costs and conserving capital, The Standard Oil Company (Ohio), in common with other oil companies, developed a program to control maintenance costs. In outline, our program consists of two broad phases. The first requires accurate and current cost figures. This meant revising and adapting our refinery accounting methods to supply maintenance information. Such statistics are necessary in a convenient form for analysis and decisive action. But—the clerical time and cost must not outweigh the value gained.

The second phase involves initiating modern industrial engineering practices. Subsequent papers at this meeting will enlarge on the following means for improving refinery maintenance:

1. Preventive-maintenance scheduling of refinery equipment.
2. Systematic planning and scheduling of maintenance man-hours.
3. Building and improving mechanical shops.
4. Incorporating maintenance facilities in process-unit designs.
5. Purchasing modern, efficient tools.
6. Training maintenance men in special skills.

This paper is devoted to the first, or control, phase of these programs. Attention is confined to methods of gathering, assimilating, reporting, and analyzing maintenance statistics and using them to *control* maintenance costs.

†Presented before a group session on refinery maintenance during the 14th Mid-Year Meeting of the American Petroleum Institute's Division of Refining, in The Shamrock Hotel, Houston, Texas, April 7, 1949.

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Definition and Purpose of Controls

The word "control" is viewed with some misgiving by many industrialists. Its use has crept into practically every human experience. We have experienced price control, wage control, rent control, material-allocation control, atomic-energy control, etc. No wonder industry looks skeptically on a program of controls!

We do not use the word in this sense of coercion or rigid regulation. Rather, the controls we propose serve to guide and direct management to correct impressions, decisions, and actions. Controls of this type stimulate unity of effort. They promote the enthusiastic aid of all management levels in the solution of maintenance problems.

Control is accomplished in three distinct steps (Fig. 1): The first is carefully planning the specific objective to be accomplished. This planning should be based on research, and on the use of previously established standards. The second step is executing the plans made. Third, the planning and the doing are appraised periodically as the work progresses. Deviations between the planned and the actual performance are brought to management's attention. Immediate and corrective steps can be taken. When the work proceeds according to plan, management need not bog itself down with the reviewing of numerous details and routines. It is the exception, not the usual, that it wants and needs. New objectives and better plans in the future result. Weaknesses in organization and in the delegation of responsibility are seen. Need for training, for faster and less costly methods, for better equipment, for organizing the work and its sequence more efficiently—these needs will stand out.

Summing up, when we speak of control, it is in terms of these three steps: careful planning to meet specific objectives; execution according to plan; and frequent comparison and investigation to gage the success of the resulting performance.

Use of Automatic Business Machines

To gather, assimilate, and report basic maintenance statistics, an automatic business-machine installation was selected. Briefly, these machines translate alphabetical and numeric data upon small punched cards, segregate *those* data that are desired, make calculations upon them, and print in report form the resulting information. Three distinct steps are involved. (Fig. 2): The first machine translates field information into record cards through the medium of punched holes. Only information put into the cards will emerge in the final reports. Therefore, some discretion must be exercised in making the initial selection. The second basic machine segregates and arranges the record cards in sequence or in groups. It uses the relative location of the holes in the punched card as its key. The third basic machine takes these sorted cards and retranslates the information from them onto a continuous paper roll. Auxiliary machines are available to supplement these basic operations. Detailed discussion of their use does not lend itself to the purpose of this paper.

1. PLANNING—to meet specific objectives.
2. DOING—according to plan.
3. COMPARING THE RESULT—looking for improvements.

FIG. 1. The three steps of control.

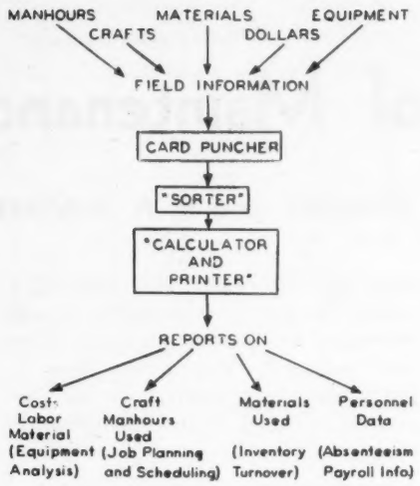


FIG. 2. Flow of maintenance statistics.

Under the previous accounting system, costs and records were kept. The clerical work was done *manually*, however. Speed was sacrificed for accuracy. Under the former cost breakdown, desired information was not secured. Preparation of reports required many clerical and typist hours. Information was presented in a stereotyped form. Desirable variations were difficult to make. Too much time and expense were required to prepare and issue cost information. The value of the reports became primarily historical.

The new installation does most of the clerical tasks automatically. Once the information is "punched into" the cards, the sorter permits selection of various combinations. Thus, from the same group of cards, we can determine:

1. The number of man-hours each craft spent on a particular job.
2. The cost of material or labor during any period.
3. Costs for each refining division, etc.

This information is available in report form in a matter of minutes. Under the old system, such information would require days to sort, accumulate, and report. The possibility of human error was ever-present. Combinations could not be changed easily. Through the automatic business machines we get current figures, in any combination desired, with little manual effort. We have multiplied the productivity of our clerical workers. We have access to information never before available. We have it when we need it, and in the form it will be best for us to use.

The machine installation is rented from a business-machine company on a monthly basis. For our various refinery installations, the rental costs and personnel requirements are as shown in Fig. 3.

Procedure for Gathering Maintenance Information

The importance of current cost figures in a rapidly changing economy is apparent. For management to make intelligent decisions; for it to take advantage of new conditions, or to recognize trends and take appropriate steps, proper information, speedily organized, is essential. Any manager engaged in guiding and directing his plant needs such assistance. If he is to hold his assistants responsible, they, in turn, must have access to cost reports to aid them. As the ladder of management is descended, the data must be more detailed and refined. The scope of attention narrows. One of the chief advantages of the automatic business-machine installation is its flexibility to meet this varying demand.

Refinery	Crude Thruput Per Day	Rental Cost/Month	No. Clerical Personnel Required
A	40,000 bbls	$1,015	6
B	20,000 bbls	$ 906	5
C	18,000 bbls	$ 740	2½
D	17,000 bbls	$ 722	4

*No material increase or decrease has been made in our total clerical force. The same personnel now prepare many additional reports for company and governmental use.

FIG. 3. Cost of business-machine installation.

Code No.	Division
	Producing Units
101	Alkylation unit
102	Asphalt manufacturing plant
103	Asphalt emulsion plant
104	Asphalt RodeRite emulsion plant
106	Cat Cracker—6 case unit
107	Cat Cracker—3 case unit
140	Rerun unit—F. O. stock
141	Rerun unit—Naphtha
142	
143	
144	Treating plant—agitators
145	Treating plant—clay filters
146	Treating plant—C/C distillate
147	
148	
149	
150	
	Refinery Operations Expense
151	Automotive equipment
152	Engineering
153	Fire protection
154	Fuel system—plant
155	Industrial relations expense
169	
	Refinery General Expense
170	
171	
172	
	Overhead Acounts
177	Service units
180	
193	Crude oil accounts
194	Working stocks—other than C.O.
195	Finished goods accounts
196	Shipments accounts
197	Miscellaneous accounts
198	Chemicals purchased accounts
199	Chemicals purchased accounts

FIG. 4. Chargeable accounts—refinery divisions.

Changes in Accounting Procedures

Before making use of these machines, however, several accounting changes were necessary. The first involved reclassifying and numbering chargeable accounts in each refinery (Fig. 4). For adaption to our business machines, the numbers began with 101. Between 101 and 150 were placed the refinery producing units, leaving sufficient unallocated numbers for future expansion. From 151 to 199 were grouped the refinery operation expense accounts, refinery general expense, overhead accounts, service units, etc. These general divisions are of interest to top-level management. Total labor and material charges by these accounts present a rapid method of comparing operating costs. Efficiency of local refinery management and of certain types of processes is quickly measured. Total refinery expense against anticipated or allocated funds is reviewed, and variations are allowed or restrained.

A further breakdown of each division is necessary for detailed study of unit costs (Fig. 5). For example, producing units are subdivided into types of equipment and materials used. Labor and material charges for each group are identified by adding two numbers to the division number; thus, the identifying number for painting repairs at the alkylation plant, "A" refinery, would be 101213 and 101223. The first 3 digits, 101, denote the particular division; the fourth and fifth digits, 21 and 22, represent repair costs for painting (the first number represents labor, the second material); a sixth digit is added to represent the refinery itself. The establishment of chargeable accounts, the determination of subdivisions for further cost analysis, and the use of identifying numbers was the first tool in our control setup. The code numbers are used principally in the accounting office as a speedy and efficient cataloging method, adapted to an automatic business-machine installation.

Gathering Field Data

The procedure for obtaining maintenance information is uniform in all refineries. A work-order system forms the basis. The use of any labor or material requires a written request. This request is made on prepared forms (Fig. 6). Each request has three important elements:

1. An identifying number, called the "work-order number."

2. A detailed description of the job requested.

3. The signature of an authorized requester.

After preparation and authorization of the written request and copies, they are forwarded to a central maintenance-department office. There the request is reviewed. The materials, crafts, and man-hours necessary for the task are estimated. On large jobs, field engineers assist with this step. Provision for the work is made in the man-hour schedule. One copy of the request is then sent to the accounting office as notice that labor and material costs will be charged to it. A clerk adds the appropriate accounting-division numbers to this copy. The task shown in the example is typical. When boilermakers begin working on this job their time is charged to the work-order number (Fig. 7). Each worker's ticket contains similar information, and is forwarded every day to the accounting office for daily tabulation and recording. When exchanger tubes are obtained from the warehouse, a requisition card is prepared, and this follows the same procedure (Fig. 8). When the work is completed, the accounting office is notified. Labor and material costs for the specific task are accumulated at desired periodic intervals. The number of man-hours spent by each craft, the number of overtime hours, etc., are tabulated, and they be-

FIG. 5. Typical cost breakdown—alkylation unit.

ALKYLATION UNIT—DIV. 101

	Labor	Mat'l	Refineries A	B	C	D
Operators	10101		3			
		10102				
	10103	10104				
Repairs—building	10105	10106	3			
Repairs—electrical	10107	10108	3			
Repairs—furnaces	10109	10110	3			
Repairs—gas compressor	10111	10112	3			
Repairs—heat exchanger equipment	10113	10114	3			
Repairs—insulation	10115	10116	3			
Repairs—machinery and equipment	10117	10118	3			
Repairs—meters and instruments	10119	10120	3			
Repairs—painting	10121	10122	3			
Repairs—piping	10123	10124	3			
Repairs—pumping units	10125	10126	3			
Repairs—structures and supports	10127	10128	3			
Repairs—tanks	10129	10130	3			
Repairs—towers and drums	10131	10132	3			
Repairs—reactor	10133	10134	3			
Repairs—	10135	10136				
Repairs—	10137	10138				

Form OW662

JOB MEMORANDUM

JOB ORDER NO. 1032

To Gen. Supt. Office
To Mech. Office ✓

STANDARD OIL COMPANY (OHIO)

Refinery "A"

Date April 1 1949

Name of Job Retubing Butane Feed - Reactor Effluent Exchanger

Unit or Area Alkylation Unit

Exact Location of Job Bundle to be brought to Boiler Shop

Equipment No. 2042

Job Description Cut out old tubes and install 3/4" O.D., 14 gage, 16'-0" long antimonial admiralty tubes in existing tube sheets

Job Type	Maintenance 1	Improvements 2	Yearly 3	Interplant 4	5
Emergency 1					
Rush 2					
Shutdown 3	✓				
Regular 4					
Estimate 5					

Order No.	Craft	
	Carpenters	
	Insulators	
	Machinists	
	Pipefitters	
	Boilermakers	✓
	Welders	
	Electricians	
	Brickmasons	
	Painters	
	Instruments	
	Transportation	
	Yard Labor	
	Storehouse	

FOR USE BY THE MECH. DEPT. ONLY

Important Process Features

Advance Notice to Process Hours/Days Latest Completion Date April 3, 1949

Significance of Job Must be finished so unit can be put on stream April 4, 1949

Signed B. Smith (Foreman or Asst. Supt.) John Doe (Process Supt. (Changes or Add.)) (Mech. Dept.)

STARTED: DATE

Completed: Date Signed

LABOR CODE 101133 COST

MATERIAL CODE 101143 COST

SKETCH OR ADDITIONAL NOTES:

Work-Order Request Form.

FIG. 6. Work-order request form.

DATE	EMP. NO.	SHIFT		CRAFT	RATE CL.	NAME
4-9-49	654 16	2	3	10		J. GREEN

JOB NO.	RATE	REG. HRS.	O.T. HRS.	AMOUNT	EST. NO.	CODE	EQUIP. NO.
1032		8	0			101133	2042
FOREMAN R. Brown		TOTAL 8	TOTAL 0	TOTAL			

HOURS RATE

DATE | EMP. NO. | S | CR. | R. C. | JOB NO. | RATE | SH. ALL | HOURS | AMOUNT | EST. NO. | CODE | EQUIP. NO.

THE STANDARD OIL COMPANY - OHIO — JOB TICKET

IBM 764141-s

FIG. 7. Individual labor ticket.

DATE	JOB NO.	ESTIMATE NO.	CODE	EQUIP. NO.	REQ. NO.
4-9-49	1032		101143	2042	

REQUISITION ON STOCKKEEPER

ITEM NO.	QUANTITY	COST EACH	COST TOTAL	DESCRIPTION
	212	$4.00	$848.00	3/4" O.D. x 14 GA. x 16'-0" LONG ANTIMONIAL ADMIRALTY TUBES

SIGNED R. Brown

DATE | NO. | CRT | JOB NO.

AMOUNT | EST. NO. | CODE | EQUIP. NO.

THE STANDARD OIL CO. - OHIO MATERIAL REQUISITION TICKET

IBM 764132-s

FIG. 8. Material requisition form.

come the basis for numerous control reports. Let us follow a typical refinery group in reviewing some of these reports. By case examples, we shall see how these reports serve as a tool for good management. The "grass-roots" approach to the problem will be clearly evident.

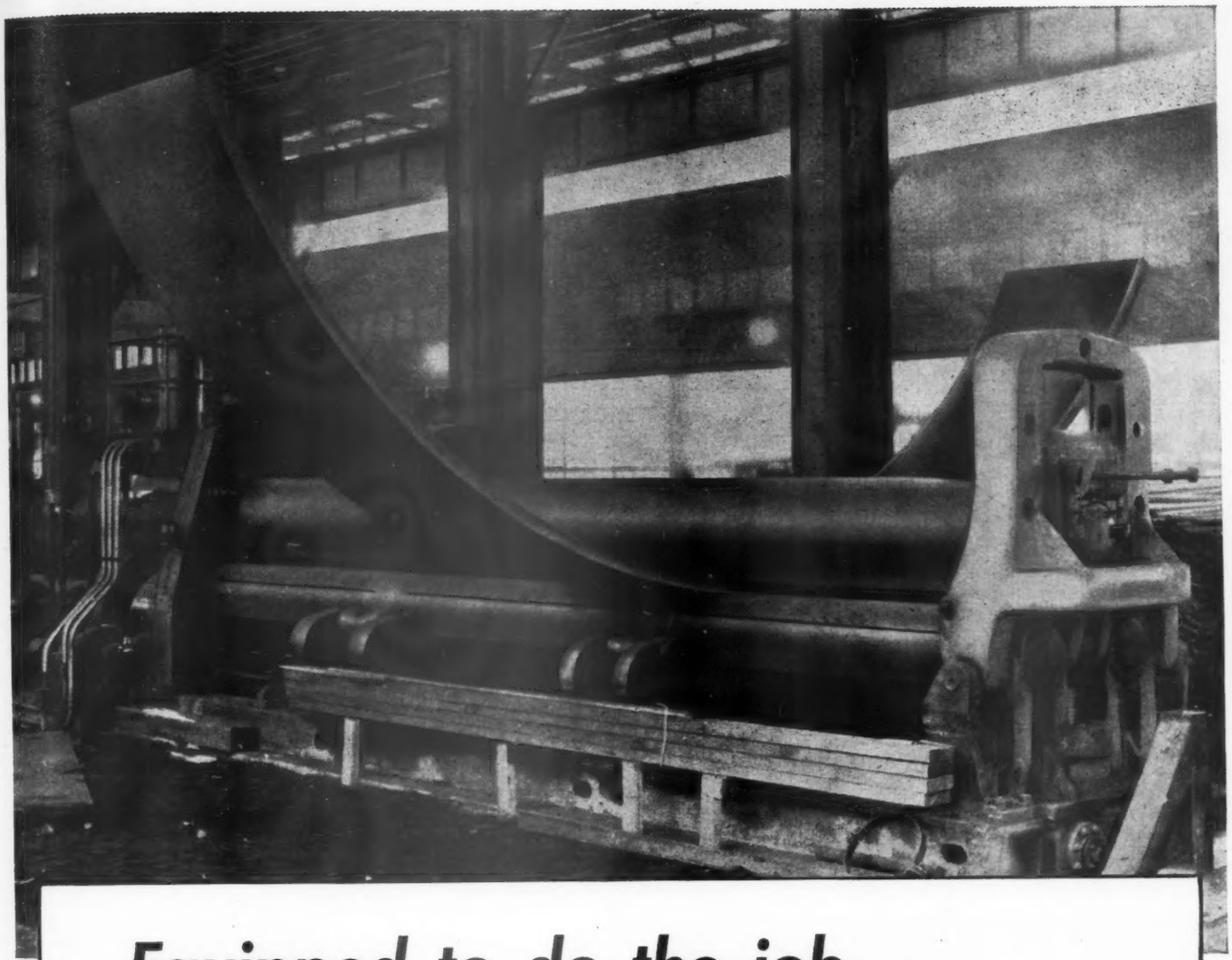
CONTROL REPORTS

Monthly Labor and Material Costs of Each Refinery Division

Each month the costs for each refinery account and subdivision are totaled. These amounts are compared with previous months, and with the average of months in previous years. Fig. 9 is an example of this report, prepared and issued monthly to department superintendents and foremen. Notice the high pump-repair costs at the alkylation unit in February and March. This report was reviewed by the maintenance superintendent, gas-plant superintendent, and maintenance engineer. They compared the pump-repair costs with those experienced in previous years. The February and March costs were four times as high as normal. No unusual rebuilding of pumps or complete replacement of pump internals occurred during this period. They did find that the pump packing was unusually troublesome, and that scored shafts and rods occurred frequently. Further investigation revealed the cause. A new helper on the unit, on his own iniative, was tightening up the packing glands so that the rods and shafts were quickly ruined; the packing, therefore, became useless. A lack of preventive-maintenance training for this new operator was the real cause, and this was soon corrected.

Maintenance Man-Hours by Crafts for Each Refinery Division

The second report, of value to plant managers, assistant managers, and mechanical superintendents, involves mechanical man-hours used. These are shown for each operating unit, and a further breakdown shows the number from each craft. Fig. 10 is an example of this report. It is of particular value in studying and comparing maintenance costs and time spent on individual units and processes. It helps to determine the work load by areas of the plant. This example points to a very high requirement for machinists. Investigation showed that the machinists' man-hours had been increasing steadily for a long period. Further analysis revealed that the sole cause of the increase was repairs to motor-operated valves on the vapor lines. Most of



Equipped to do the job

Sun builds made-to-order units for all refinery and chemical plant processes. Sun also furnishes repair services and parts. This is evidence of the vastness of Sun facilities, facilities that include rolls so powerful as to be capable of cold bending steel sheets 3½" thick . . . Having similarly extensive facilities for shipbuilding, Sun turns out record-making tankers and cargo vessels from keel to superstructure—no subletting.

Sun

SHIPBUILDING & DRY DOCK COMPANY

SINCE 1916

ON THE DELAWARE • CHESTER, PA.

25 BROADWAY • NEW YORK CITY

Alkylation Unit	1949 Jan.	Feb.	Mch.
Operators	$3,019.81	$2,629.98	$2,252.52
Repair buildings—labor	115.05		
—material	101.28		
Repair electrical—labor	214.62	113.14	125.97
—material	72.47	54.47	24.17
Repair heat exchangers—labor		212.00	
—material		484.00	
Repair piping—labor	66.43	311.62	199.12
—material	28.56	252.98	35.55
Repair pumping units—labor	240.60	980.30	1,104.60
—material	210.80	890.40	1,090.50
Repair tanks—labor	83.56		20.71
—material	14.07		

FIG. 9. Monthly labor and material costs—alkylation unit.

these repairs were found to be in the gear mechanism, and these in turn were due to using the wrong lubricant. At some time in the past the lubricant provided had been changed from that originally specified, and the substitute did not perform the required services. This example demonstrates the use of reports to trace a costly maintenance problem and to effect a solution.

Total Man-Hours by Work-Order Types

As any maintenance superintendent will testify, some refinery divisions seem to require a disproportionate amount of emergency and rush work. Keeping this type of work to a minimum results in better job planning and scheduling. As a control in this direction, a distribution is made of total man-hours spent for each division by emergency, rush, routine, or shutdown work orders. This check restrains such emergency and rush orders. Chronic offense may indicate inadequate preventive maintenance, improper equipment, or poorly trained mechanics. Fig. 11 illustrates a typical example of this report. Notice that the emergency and rush man-hours on the "cat cracker" were almost two-thirds of the routine man-hours spent on maintaining this unit. The maintenance superintendent and process superintendent were determined to find the reason. Analysis showed that the situation had prevailed for several months. Furthermore, almost all of the emergency work was on the unit's gas compressors. Additional facts secured showed that the preventive-maintenance schedule set up for these units was not being followed. An increase in throughput had used up the spare compressor capacity. The scheduling no longer allowed for an adequate time for proper preventive-maintenance operations. Inasmuch as the higher throughput was scheduled to be maintained and increased further in the future, this investigation led to the decision to install an additional gas compressor on the unti.

CATALYTIC CRACKING UNIT
Month Ending March 31, 1949

Craft	Craft No.	Manhours
Boilermakers	10	2,160
Welders	11	730
Machinists	13	5,860
Painters	14	920
Pipe Fitters	15	3,270
Instrument	23	1,880
Laborers	26	4,120
Total		18,940

FIG. 10. Maintenance man-hours by crafts.

Labor and Material Report for Unit Shutdown

The shutdown of refinery units for periodic inspection and repair is costly. Downtime must be held to a bare minimum. The time must be efficiently planned and scheduled beforehand. These plans and schedules must be carefully reviewed while the work is in progress and after the unit is back on stream. Improvements and better methods must constantly be sought. Through such comparison, we have uncovered bottlenecks in man-power allocation and equipment efficiencies. Fig. 12 shows a typical report and two case examples. Notice that the overtime hours required of craft No. 26 were three-quarters of the regularly scheduled hours for unplugging furnace headers. The analysis of this problem was quite simple. The crew scheduled for the work had proper and efficient tools. By working regular hours, however, they could not finish this operation before the next scheduled operation. Inasmuch as the time could not be changed without length-

Week Ending April 8, 1949

Div. No.	Division	Emergency	Rush	Routine	Shutdown
101	Alkylation unit	140	30	650	—
106	Cat cracker—6 case	2448	750	4810	—
111	Cat poly plant	420	80	1200	—
116	Cracking coils	530	610	2040	—
117	Cracking coils	420	110	2460	—
122	Thermal gas plant	210	410	1004	—
132	Pipe Still	360	100	1260	—

FIG. 11. Total man-hours by work-order types.

Work Order No.	Description	Craft No.	Reg. Hrs.	O.T. Hrs.	Labor $	Mat. $
24666	Unplug Headers, Furnace	10	13.00	1.00	29.80	
		11	18.50	41.00	161.10	
		12	4.00	22.00	85.64	
		22	1.00	1.00	5.32	
		26	454.50	322.75	1448.10	
		29	1.00	.....	2.06	
		31	1.00	1.00	5.32	
						318.33
			493.00	388.75	1737.34	
24667	Turbine Furnace Tubes	10	28.50	3.00	67.97	
		11	.50	5.00	16.48	
		12	3.00	2.00	12.36	
		15	11.00	14.00	65.96	
		22	4.00	.....	8.49	
		26	267.25	253.00	971.05	
		27	8.00	1.00	17.30	
		28	3.00	.....	5.90	
						100.46
			325.25	278.00	1165.50	

FIG. 12. Shutdown No. 95—combination unit, "A" refinery.

VESSEL DIVISION

NEWS

A.O. Smith 75th ANNIVERSARY 1875 - 1949

A. O. SMITH Corporation

New York 17 • Philadelphia 3 • Pittsburgh 19 • Atlanta 3 • Chicago 4
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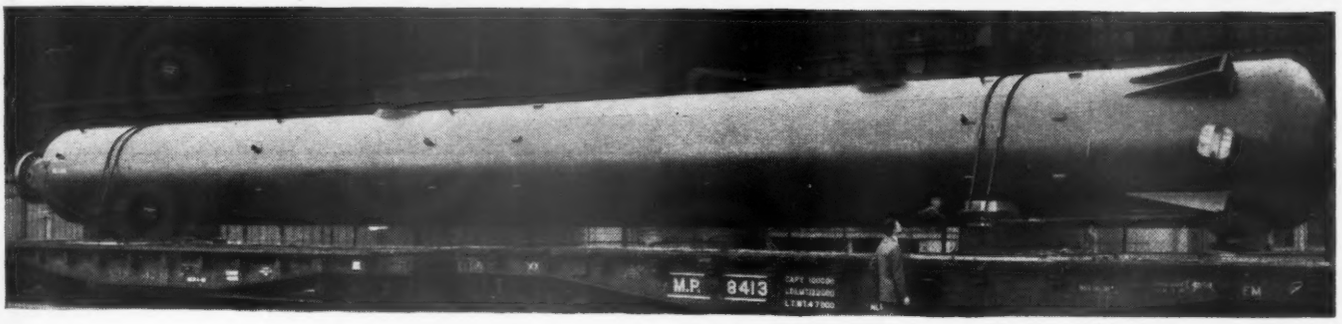
VESSEL LIFE INSURANCE. Before this SMITH-lined Paper Mill Digester was manufactured, an extensive and comprehensive testing program was completed to be sure the proper alloy lining was selected for the corrosive service. An experimental digester was built and a great many "cooks" were run before the final decision was made.



USING SMITHway MULTI-LAYER CONSTRUCTION WAS MORE ECONOMICAL than single-plate construction in the manufacture of this 72 in. dia. by 80 ft. long water scrubber, at the same time providing a safer construction.

CONSISTENT QUALITY OF SMITHway ELECTRODES used in the manufacture of SMITHway Pressure Vessels is preserved by meticulous control procedures. By means of this X-ray diffraction machine, all raw materials used in electrode coating are checked for the presence of any foreign materials or impurities.

FIELD ASSEMBLY COSTS CUT TO A MINIMUM. The SMITHway is to do the maximum amount of work possible in the shop on vessels too big to be shipped in one piece. All the shell courses on this 15 ft. dia. by 113 ft. long SMITHway Atmospheric Tower were tacked together in the shop to get more accurate and complete installation of the internals.

SEND FOR THESE NEW BULLETINS

Write the nearest A. O. Smith office (see list at top of page) for these newest Vessel Bulletins:

•

FIELD ASSEMBLY OF PRESSURE VESSELS—Bulletin V-44.

•

SMITHway VESSELS — Alloy, Alloy-lined, Clad, and Glass-lined —Bulletin V-46.

ening the total shutdown period, the solution was to put two gangs on the job instead of one.

The second case example shown concerns craft No. 26 on turbining furnace tubes. Note that the overtime hours for this requirement were almost equal to the regularly scheduled hours. The maintenance superintendent knew that the condition of the tools would have a strong influence on the time required for turbining the tubes. Therefore, this point was investigated first. It was found that the tools were in excellent condition, but did not seem to cut out the coke as rapidly as a similar type of coke on another unit. The maintenance engineer suggested that an air pressure gage be installed immediately ahead of the tool. That suggestion hit the bull's eye. Instead of the 100-lb required air pressure, there was available only 70-lb when the tool was operating. The cause of the high overtime and expense in this case was an inadequately sized air line from the main header to the furnace. This example also shows the value of having man-hour data available from previous shutdowns. The actual hours required for particular representative operations can be secured. This information makes more accurate the preparation of schedules for the next shutdown. It contributes to a better job of planning and scheduling activities, to be discussion by others on his program.

Incomplete Work-Order Listing

As a further aid to controlling maintenance, a monthly incomplete work-order listing is made. At a glance, it is possilbe to determine whether work is accumulating, or if the backlog is only normal. Fig. 13 shows a portion of this report. It points to incomplete jobs which are allowed to drag. They just do not "hang fire" for several months when subjected to a listing and periodic review. The reviewer's attention is also directed to the reasons for a job delay. For example, the maintenance superintendent wondered why no work had been done in March on work order No. 10016: "Install new roof on tank No. 69." He knew that work on this job had begun in February. His investigation showed an inadequate inspection procedure to determine the extent of work necessary. When the old roof was torn off, it was found that the top angle on the shell had corroded to the point that it would have to be replaced before the new roof was put on. The proper size angle was not available immediately; therefore, the whole job had to wait until it could be secured and rolled to the correct curvature. Next time a roof is to be replaced, the inspectors will make certain that the top angle and top shell sheet also do not require repair and replacement.

Month of March, 1949 "A" Refinery

Work Order No.	Description	Craft No.	Regular Hours	Month's Labor Cost $	Total Labor Cost To Date
10214	Retube spare exchanger No. 407	10	78.00		
		11	40.00		
			118.00	243.08	243.08
10204	Renew valve manifold at No. 1 pumphouse	17	204.50	421.27	670.30
10016	Install new roof on tank No. 69	....	.....	.....	160.30
10170	Install new gas compressor	10	110.00		
	Catalytic cracking unit	26	480.00		
			590.00	946.60	946.60

FIG. 13. Monthly run of incomplete work orders.

3-Month Period Ending March 31, 1949 "A" Refinery

Work Order No.	Description	Craft No.	Reg. Hrs.	O.T. Hrs.	Labor $	Mat. $
447	Inspect instruments at cracking coils	23	160.00	20.00	394.72	62.60
1231	Inspect instruments at alkylation unit	23	1860.00	483.00	5280.60	1040.60
2407	Inspect instruments at thermal gas plant	23	115.50	37.00	384.93	104.90

FIG. 14. Blanket work orders.

"A" Refinery

Work Order No.	Description	Craft No.	Reg. Hrs.	O.T. Hrs.	Labor $	Mat. $
11764	Installation of new depropanizer	10	63.00		116.40	
	reflux pump, alkylation unit	12	34.00		66.30	
		13	78.00		142.70	
						755.18
			175.00		325.40	
14697	Renew 12" valve manifold at	10	46.00		91.30	
	main pump station	11	88.00		174.20	
		13	8.00		16.48	
		15	135.00		248.32	
						260.60
			277.00		530.30	
13211	Install new reflux condenser,	10	160.00		304.00	
	cat cracker stabilizer	15	24.00		45.60	
						2290.00
			184.00		349.60	

FIG. 15. Completed work orders, April 1 to April 15, 1949.

Blanket Work-Order Costs

Some work in refineries consists of minor tasks on which individual costs would not be significant. More clerical and paper work would be required to record such costs than the individual amounts merit. For example, checking and inspecting control instruments in the plant may total a thousand different jobs. No advantage is gained by a separate work order written and processed for each. Instead, a work order is written to check and inspect all control instruments in each account division. For example, the order says: "Check and inspect all control instruments at the alkylation unit." This order remains effective for a period of time, ordinarily three months, to cover the preventive-maintenance schedule on this unit's control instruments during that period. Periodically the costs accumulating against such work orders are reported and reviewed. Large amounts which are out of line with normal experience are investigated in detail. Fig. 14 illustrates a blanket work-order report. When the mechanical superintendent, maintenance engineer, alkylation-unit foreman, and instrument foreman reviewed this report, they noted that the

PUMP NO. 204 7½x5x10 DUPLEX PUMP CLAY CONTACT PLANT

Date	Labor $	Material $	Description of Repair
1-20-48	148.50	153.80	New pistons, rings, and rods (liquid end) and new liners
2-10-48	25.80	30.60	3 new valves, 2 springs (liquid end)
3-30-48	38.80	42.30	2 new rods and new gland (liquid end)
4.18-48	110.60	48.30	Renewed liners (liquid end)
5-12-48	62.90	54.70	New piston, rings, and rods (liquid end)
6- 3-48	90.60	70.60	Replaced liner, installed new valves and springs
--	477.20	400.30	Total six-month cost

FIG. 16. Equipment record card.

instrument-inspection costs at the alkylation unit were disproportionately high in relation to the number of instruments in use. A check with instrument repairmen and the unit process operators revealed that many daily adjustments were necessary, and that the reliability generally was poor. The problem then became one of finding the reason. It was discovered that vibrations from an adjacent gas-compressor building were being transmitted through the ground to the instrument panel board. These vibrations were continually upsetting the operation of the control instruments. A special panel-board mounting, designed to absorb the vibrations, quickly reduced the instrument maintenance on this unit to a normal amount.

Completed Work-Order Costs

Twice a month a list of completed job orders is prepared. Foremen receive copies showing the cost of labor and materials of individual jobs. Costs which are out of line with estimated amounts are checked. Poor planning of the work and inadequate supervision have been primary causes. Review and examination of these reports (Fig. 15) help the supervisors to follow their work more closely and to do it more economically. This example contains a job on which there was poor planning: "Install new reflux condenser, cat-cracker stabilizer." The labor required by craft No. 10, the boilermakers, seemed to the mechanical superintendent far out of line with the scope of the project. The job merely involved lifting the new reflux condenser onto existing steel work and bolting it down. The pipe fitters would then hook it up. He reviewed the project with the boilermaker foreman, and soon discovered poor planning and scheduling. Advance arrangements had not been made with the transportation-equipment department to have a crane available to do the hoisting work. The day could not be changed because the stabilizer was shut down to make

Week Ending March 25, 1949

Craft	Craft No.	Overtime Manhours
Boilermakers	10	140
Welders	11	60
Insulators	12	20
Machinists	13	620
Painters	14	30
Pipe fitters	15	320
Instruments	23	280
Laborers	26	460
		1,930

FIG. 17. Overtime man-hours by crafts.

the installation. Because the hoisting crane was tied up elsewhere, the boilermakers used chain hoists to mount the condenser on the steel work. The cost of doing the job this way was about three times higher than if the hoisting crane had been used.

Individual Equipment Costs

Costs of maintaining and operating specific pieces of equipment are especially helpful in making repair and replacement decisions. Excessive costs might indicate improper maintenance, application, or design. Individual pumps, compressors, automobiles, cranes, motors, etc., are subjected to such analysis. Fig. 16 shows a typical record kept of repairs made to a pump in service in one of our refineries. The date, costs, and complete description of all maintenance work are kept. The pump shown in this example is a duplex reciprocating-type used to pump clay oil slurry at a clay-contact plant. Review and investigation of these high maintenance costs showed that this type of pump was improper for the service. The maintenance costs for one year were almost twice the cost of an especially designed centrifugal pump which has been a trouble-free replacement.

Report of Craft Overtime Man-Hours

In all our refineries we attempt to keep overtime man-hours to a minimum. As a check on the success of this effort, a list of overtime hours by crafts is prepared weekly. Attention is thus directed to unbalanced work forces, poor planning, and to crafts needing additional man-power. A sample of this weekly report is shown in Fig. 17. When a particular craft continually runs a high percentage of overtime hours, an investigation is made to determine the cause, and the necessary correction is made.

Cost Reports of Estimates

Up to this point the discussion has centered around operating costs and expenses incurred in day-to-day operation in the refinery. Also important is the control of specific appropriations of money made by the company management. Most companies require top-level approval of expenditures over a certain amount. Our company calls these projects "estimates." It is important that the amount allocated is not exceeded; hence, periodic progress reports on these estimates are essential for management control. Fig. 18 is a

FIG. 18. Estimate progress report—labor charges.

"A" REFINERY

Month Ending December 31, 1948

Est. No.	Description	Craft Number	Manhours	Labor for Month $	Accumulated To Date
80-334	Gas plant revamp				
	a) Dismantling	10	80	164.80	300.00
		12	160	329.60	550.00
					850.00
	b) Foundations for towers	10	2120	4367.20	28,460.00
		26	4150	6240.00	17,300.00
					45,760.00
	c) Piping	12	.....	.....	.....
		20	.....	.....	.....

typical management report. Current labor expended to date on each job is shown. From these reports and the status of the field work, the maintenance supervisors and engineers prepare the report shown in Fig. 19. Trends to overexpend the amount appropriated serve to give advance notice to management for supplemental appropriations, or revision, or cancellation of the project. Estimation of costs in advance is bound to be partly contingent, but the periodic control reports do discover high costs and permit management to ask: "Is the job poorly supervised, incorrectly engineered, or inaccurately estimated?" Let us look at a typical example, viz., Estimate E-334: "Gas-Plant Revamp." The control report shows that this project will be overexpended $64,000, or 16½ per cent, and that this fact was known when the job was only a third complete. Investigation showed that the cause in this case was inadequate preliminary engineering. When field work was begun on the foundations for additional gas-plant fractionating towers, it was discovered that the allowable soil-bearing pressure was so low that piling was required. The installation was made adjacent to an existing plant where the soil-bearing pressures did not require such piling. Nevertheless, the engineering department was in error in not making sure that a similar condition existed on the site for the new equipment.

"A" REFINERY Dec. 31, 1948

Est. No.	Date of Approp.	Project Name	Amount Approp.	Estimated Final Cost	Estimated Overrun	Estimated Underrun	Estimated Completion Date	Est. % Comp. To Date
80-334	4-28-47	Gas plant revamp	$390,000	$454,000	$64,000	.....	8-1-49	35
80-377	9-23-47	Replace 2, 3 & 4 C/S exchangers	29,334	25,458	.....	3,876	1-1-49	100
80-389	10-29-47	Cafeteria—locker building	225,000	207,190	.....	17,810	2-1-49	95
80-414	3-11-48	Firewater loop at north end of property	4,000	2,432	.....	1,568	2-1-49	90
80-421	4- 1-48	Misc. tools—shop equipment	4,700	4,401	.....	299	2-1-49	90

FIG. 19. Estimate control report.

"B" REFINERY Aug. 31, 1948

Item	Size	Unit	Code	April	May	June	Total Usage	Inventory 8-31-48
Insulation BH-1 Plastic		Lb	131576		104	100	204	75
Pine, White	1"x8	Ft	150531		465	249	714	759
Elbows 45D B.M.	2	Ea	201909	24	18	18	60	54
Schedule 40 Pipe	2"	Ft	304001	180	240	980	1400	760
	4"	Ft	304002	340	510	811	1661	1030
	6"	Ft	304003	1090	980	960	3030	2570
Schedule 80 Pipe	2"	Ft	304011	210	290	740	1240	860
	4"	Ft	304012	410	680	1050	2140	1040
	6"	Ft	304013	1280	1620	2260	5160	2900

FIG. 20. Warehouse inventory—material turnover.

Inventory Control Report

A final type of report is shown in Fig. 20. We are experimenting with reporting material inventory on the new business machines. At present our refinery storehouses manually post material receipts and disbursements. Such records are kept on a card system. To determine advantages and disadvantages of preparing inventory reports on business machines, the form shown in the example is used in one refinery. We have not yet decided on the merits of this procedure.

Conclusion

Statistical controls are convenient tools by which modern management guides and directs its far-flung operations. Controls can provide means for securing effective and improved performance. Their importance rests on their adaptability to the actual area of operations. We have demonstrated the type of control one business-machine installation makes possible in our refineries. It also performs, more economically than any other method, accounting duties such as preparing the payroll register and payroll checks, personnel reports, etc. This phase has not been discussed. Rather, we have emphasized the application to refinery maintenance. The forms of the reports themselves are changing in our search for the best arrangement and association of data. The flexibility of the installation makes such changes simple, and at no additional cost. No special operators' skills are required. Yet the information gained is essential to the economical and resourceful operation of our refineries.

We have illustrated the following types of control reports:

1. Labor and materials for maintaining and operating every producing and service unit in the refinery, and also the expenses accrued by each refinery account.

2. Expenditures of labor and material further subdivided by type of equipment, period of time, and amounts of material used.

3. Labor expenditures tabulated by individual jobs, crafts involved, manhours, individual piece of equipment, and amount of overtime.

Other papers at this session will emphasize specific programs for improving maintenance. The application of our types of controls is easily seen. They quickly gage the success of any other maintenance programs. No matter whether the care of your equipment is insured by way of a preventive-maintenance program, or whether better mechanical shops are provided, or whether your maintenance work is organized through job planning and scheduling, the ultimate goal is to increase the productivity of your equipment and your workmen. In that goal your consumers benefit, your employees benefit, and your stockholders benefit. By providing your refinery management with the proper tools and methods, its responsibilities will be discharged competently. Better maintenance methods result in reduced costs, and they conserve capital. Energy and capital are then available to meet new challenges and to fulfill future obligations. The success of the oil industry in the past is outstanding. The application of vision and ingenuity to refinery maintenance is necessary to insure continuance of that success.

* * *

Note: The International Business Machine Company has supplied the automatic business-machine installations in our refineries. The work-order form, job ticket, and material-requisition cards were prepared by the International Business Machine Company for use in these installations.

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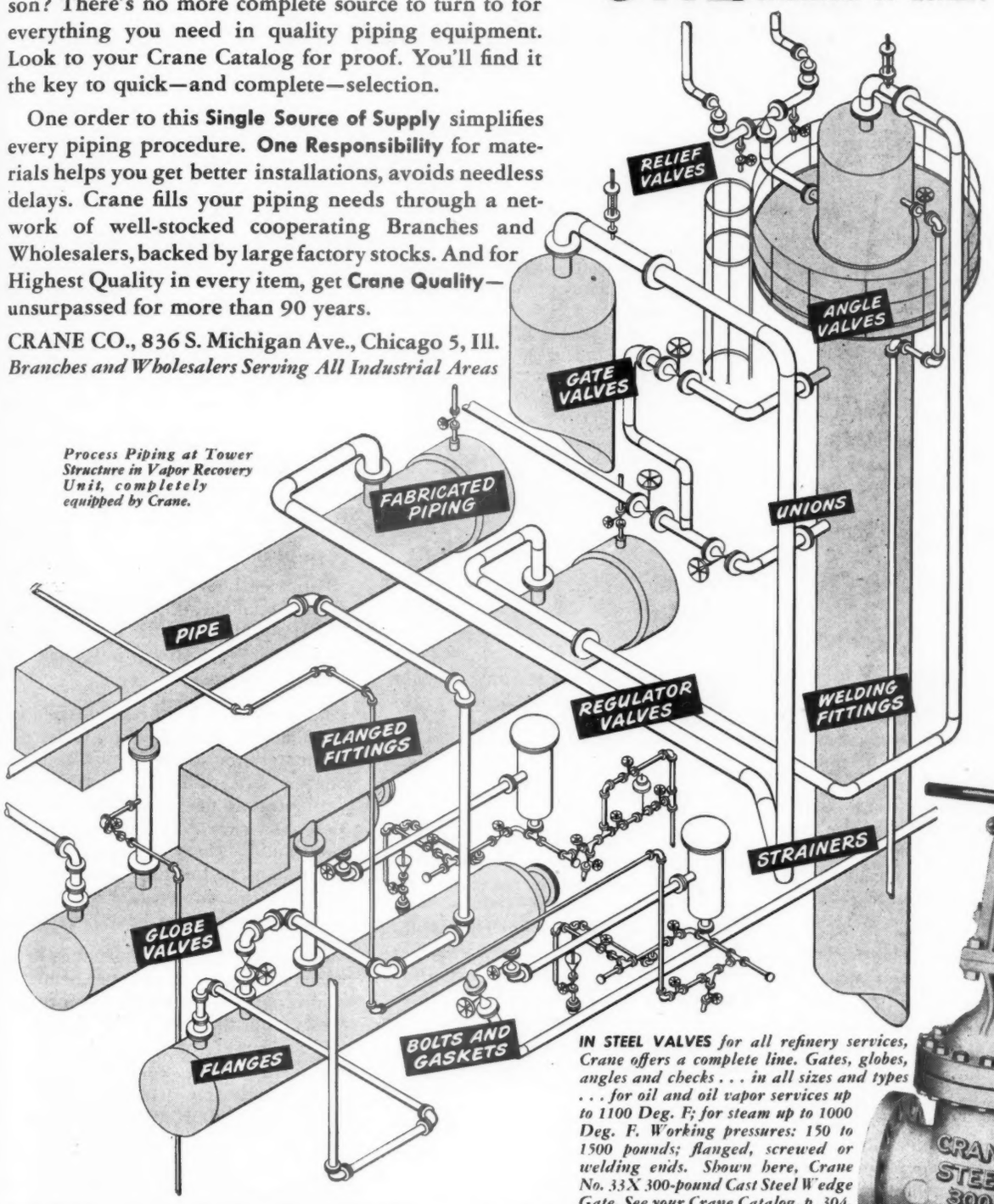
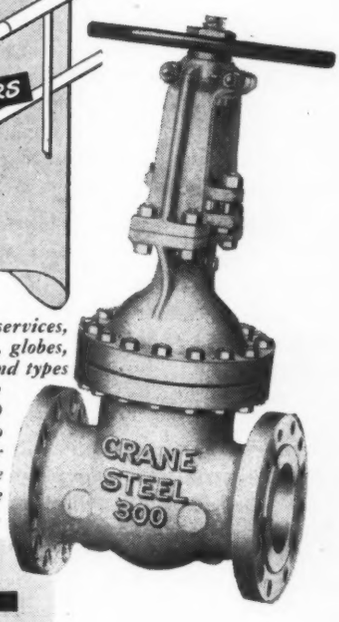


Process Piping at Tower Structure in Vapor Recovery Unit, completely equipped by Crane.



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pH Control Through the Use of a Sulphur Burner-Elimination of Scale and Prevention of Delignification in Cooling Towers and Similar Equipment.

R. C. ULMER† and J. F. CHURCHILL‡

Introduction

MILLIONS of dollars are spent yearly in cleaning and replacing equipment in cooling water systems. In addition, owing to decreased heat transfer in the case of "dirty" equipment, there are further losses either in efficiency or capacity amounting to still greater sums. Fortunately, in recent years a better understanding has been reached regarding these problems and improvements are possible. It is the purpose of this paper to review this information.

The Problem

In discussing cooling water problems we refer to any case where water is circulated through or over equipment to absorb or carry away heat. The chief types of equipment involved are cooling towers and related equipment for example in the petroleum field, engine jacket systems, refrigeration systems, steam condenser systems, air conditioning systems, etc. The systems referred to involve at least three types of cooling water systems which can be classified as follows:

1. Once-through systems.
2. Open circulating systems.
3. Closed circulating systems.

The names pretty much indicate the difference between the systems. Fortunately the problems involved are about the same for all three systems and are as follows:

(a) *Scale and Deposit Formation.* Whenever water is heated or concentrated, there is a tendency for materials to come out of solution or precipitate. The materials that precipitate may come out of solution on heating surfaces forming scale or some of the precipitated material suspended in the solution may deposit on the heating surfaces. In either case, decreased heat transfer rate occurs and therefore lower efficiency results. This is probably the most important problem encountered in such systems.

The chief material that precipitates when water is heated or concentrated is calcium carbonate ($CaCO_3$). Some difficulty is also encountered from the precipitation of iron oxide (Fe_2O_3). Both materials result from constituents that are normally soluble in the water. Whether difficulty will be encountered from the precipitation of these materials depends greatly on the pH solution. Most of the corrective measures for the prevention of scale and deposit in cooling water systems center around the elimination of the precipitation of these materials or upon the prevention of adherence of any of the materials that precipitate.

(b) *Corrosion.* Since most waters contain dissolved oxygen and carbon dioxide, both of which have a tendency to cause corrosion, this problem is often encountered and is discussed later in greater detail. The problem of corrosion is usually combatted by proper pH adjustment.

(c) *Algae and Slime.* This problem is so well known that it requires no explanation. Needless to say, during the "growing season" formation of such growths becomes a real nuisance and large losses result from decreased efficiency and capacity.

(d) *Delignification.* This is an apparent rotting of the wood, the lignin and cellulose products being extracted leaving the wood in a stringy mass having little if any strength. This difficulty is caused almost entirely by the action of alkali on the wood. Proper control of the alkalinity or pH therefore is the chief means used to combat the problem.

Previous Corrective Means

The chief factors that affect scale or deposit formation are temperature, rate of heat transfer, calcium, magnesium, silica, sulphate, and alkalinity concentrations, and especially pH value. Considerable work has been carried out to relate these factors to the problems encountered. By means of Langelier's equations, which take into consideration pH, calcium, total alkalinity, dissolved solids, and temperature, it is possible to predict with some degree of accuracy whether a water is scale forming or corrosive. The Langelier index is well known in this respect. The basis of the index is whether or not water is saturated with calcium carbonate. If it is, there of course is danger of deposit formation. If it is not, there is little if any danger of deposit formation, but there is danger of corrosion.

Some success has been experienced through the use of this index, but unfortunately its determination and calculation are rather involved which eliminates its use as a field method. Also, it is very difficult to adjust the condition of the water so that it is just non-scale-forming and at the same time not corrosive. For this reason other procedures have been used.

By far the most emphasis has been placed on the use of specific chemicals to prevent the precipitation of materials from the water. The chemicals used are largely of the complex phosphate type. None are 100 per cent efficient and some deposits will form, especially if the pH exceeds 8.0 to 8.5. This has led to the incorporation of organic materials along with the phosphates to condition the material that does precipitate so as to make it non-adherent. Again it should be noted that the success of this method depends largely on pH control. In other words, the system is effective only if pH is below the range given. Sulphuric acid and other acidic materials have been used to some extent in an effort to control pH, but their usage has not

*Presented before California Natural Gas Association Meeting in Los Angeles, September 2, 1948.

†Technical Director.

‡West Coast Divisional Manager.

been generally accepted owing either to hazards involved or to cost.

These chemicals also are advocated to eliminate corrosion if the pH is so low that corrosion will take place, for example, below 7.5. Needless to say, such a low pH in the cooling water itself is seldom encountered.

With respect to delignification, little attention has been given to this problem until recently. Fortunately, as discussed later, the remedy is very simple.

Recommended Corrective Means

A consideration of the short-comings of the previous corrective means referred to, together with the results of investigative research has led to the adoption of the use of an effective anti-precipitating agent in conjunction with a sulphur burner to control pH for the elimination of cooling water problems. A photograph of the essential equipment involved is shown in Fig. 1, and Fig. 2 shows a line diagram of a typical installation. Referring to Fig. 2, it will be noted that the essential equipment consists of a sulphur burner for forming sulphur dioxide, and an absorption tower for absorbing the sulphur dioxide in the cooling water. The anti-precipitating agent is fed into the effluent from the absorption tower.

The actual construction, design, and usage of the sulphur burner is discussed in greater detail in a bulletin dated 1-12-48 RCU, titled, "Scale Prevention and Alkalinity Control Through the Use of a Sulphur Burner." These bulletins are available upon request.

The burner is so designed and constructed as to require little care. In fact, once the burner is in operation, all that is necessary is to fill the sulphur hopper once a day or so and to adjust the air supply. Either a compressed air line or a blower can be used to supply the air. The amount of air passed through the burner chamber governs the amount of sulphur burned and consequently the amount of alkalinity reduction. The leveling of sulphur in the burner chamber is automatic, all that is necessary being to adjust the gas flow through and around the hopper so as to maintain the molten sulphur in a certain temperature range. A by-pass valve is provided for this purpose. The gas passes from the burner to the absorption tower. A part or all of the water from the heat transfer equipment may be passed through the tower. The tower will handle 100 gpm satisfactorily. This makes possible treating very large volumes of water, for example, such as involved in large cooling towers or in large boiler plants since only a small fraction need be passed through the burner-tower combination.

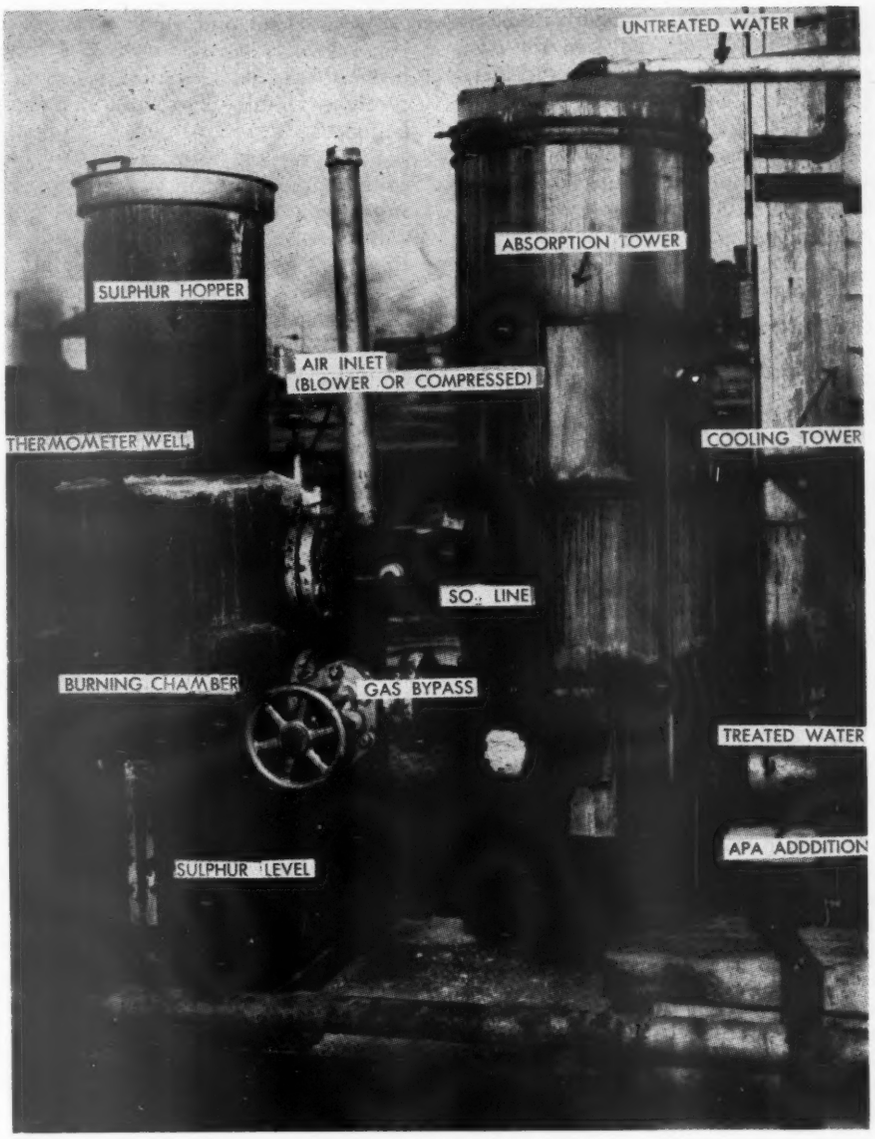


FIG. 1. Typical set-up for sulphur burner. APA treatment of cooling tower.

The burners are currently available in three sizes. The large one will burn 3 to 15 lb of sulphur per hr; the medium size one one to five lb of sulphur per hr and the small one 0.2 to 1 lb of sulphur per hr. On the basis of sulphuric acid this corresponds in the case of the large burner to the use of 12.4 to 46.5 lb of sulphuric acid per hr; the medium sized burner to the use of 3.1 to 15.5 lb of sulphuric acid and in the case of the small burner to the use of 0.62 to 3.1 lb of sulphuric acid per hr. Larger burners can be supplied or several of the large size can be used in case more capacity is required.

From a chemical standpoint, in the burner the sulphur is burned to sulphur dioxide—

$$\underset{\text{Sulphur}}{S} + \underset{\text{oxygen}}{O_2} \longrightarrow \underset{\text{Sulphur dioxide}}{SO_2}$$

The sulphur dioxide dissolves in the water in the absorption tower forming sulphurous acid—

$$\underset{\text{Sulphur dioxide}}{SO_2} + \underset{\text{water}}{H_2O} \longrightarrow \underset{\text{Sulphurous acid}}{H_2SO_3}$$

The sulphurous acid formed reacts with any alkalinity present, for example sodium bicarbonate or calcium bicarbonate, neutralizing it—

$$\underset{\text{Sodium bicarbonate}}{2NaHCO_3} + \underset{\text{Sulphurous acid}}{H_2SO_3} \longrightarrow$$

$$\underset{\text{Sodium sulphite}}{Na_2SO_3} + \underset{\text{Water}}{2H_2O} + \underset{\text{Carbon dioxide}}{2CO_2}$$

In reducing alkalinity 0.32 ppm of sulphur when burned will neutralize 1 ppm of alkalinity expressed as calci-

um carbonate. Consequently, 0.32 lb of sulphur will be required for each ppm of alkalinity reduction desired for each 1,000,000 lb of water involved. Expressed on the basis of 1000 gal, this amounts to 0.0027 lb of sulphur per ppm alkalinity reduction desired per 1000 gal of water involved.

Approximately 3.1 times by weight as much sulphuric acid as sulphur is required for alkalinity reduction. Currently sulphur costs about 0.9 cents per pound and sulphuric acid about 1.6 cents per pound. Consequently, 0.9 cents worth of sulphur will reduce as much alkalinity as 4.9 cents worth of sulphuric acid. On a million pounds of water basis, following are the pertinent data on the relative costs per ppm reduction:

	Sulphuric acid	Sulphur
lb per ppm reduction per 1,000,000 lb H_2O	0.99	0.32
Cost cents per ppm reduction per 1,000,000 lb H_2O	1.6	0.29

Consequently, it is obvious that in addition to being more convenient and safe to use, sulphur through the use of the sulphur burner is much cheaper than sulphuric acid for alkalinity reduction. Thus pH control is possible and practical, and when the burner is used in conjunction with a proper anti-precipitating agent, scale and deposit formation and corrosion will be eliminated. It should be noted that through the use of the sulphur burner proper, pH control is made possible without the hazards and high costs normally involved in previously used methods.

As to algae and slime control, in general fairly satisfactory results have been obtained with materials currently available. The chief materials being used are chlorine and compounds based on chlorine, phenates or compounds based on phenol, copper sulphate, and more recently bromine and complex ammonium compounds. In some cases the organisms build up a tolerance to any one of the materials listed, in which case it may be necessary to switch to one of the others for a short period.

Although too recent for any definite conclusion, there are indications that the use of the sulphur burner will decrease or eliminate the growth of algae and slime. At present it is not known whther the action is one of toxicity or of decreased oxygen content. In any case, in the installations made so far it has not been necessary to use supplementary treatment for algae control.

As mentioned previously delignification of wood is eliminated and prevented through the control of pH with the sulphur burner. A pH of 8.0 to 8.5, which is necessary in any case for scale prevention, insures little if any attack on the wood.

Operating Data

Following are typical data for plants operating with the sulphur burner. Plant A is in the California area and Plant B in the Texas area.

In the case of Plant A before the use of the sulphur burner, practically every type of treatment was tried but bad scaling occurred because of the high pH. After starting use of the sulphur burner in conjunction with anti-precipitation treatment, the old scale gradually disappeared and no new scale was formed. Also, no corrosion or algae has been experienced.

Plant A.

	Make-up	Main tower*	Main tower**
pH	7.6	8.0	7.5
Phenol-alkalinity ($CaCO_3$)	0	0	0
Total alkalinity ($CaCO_3$)	260	350	99
Hydrate alkalinity ($CaCO_3$)	0	0	0
Total Hardness ($CaCO_3$)	499	1950	1150
Chlorides (Cl)	49	208	103
Sulphates (SO_4)	531	2400	1408
Silica (SiO_2)	19	70	43
Phosphate (PO_4)	0	4	5

Note; Results are in ppm.

*Operating as single unit.
**Operating with some tower water used as make-up for 5 other towers.

Plant B.

	Raw	Main tower basin
pH	7.8	8.2
Phenol-alkalinity ($CaCO_3$)	0	0
Total alkalinity ($CaCO_3$)	190	200–300
Total hardness ($CaCO_3$)	105	700–800
Chloride (Cl)	33	120–180
Sulphate (SO_4)	8	540–750

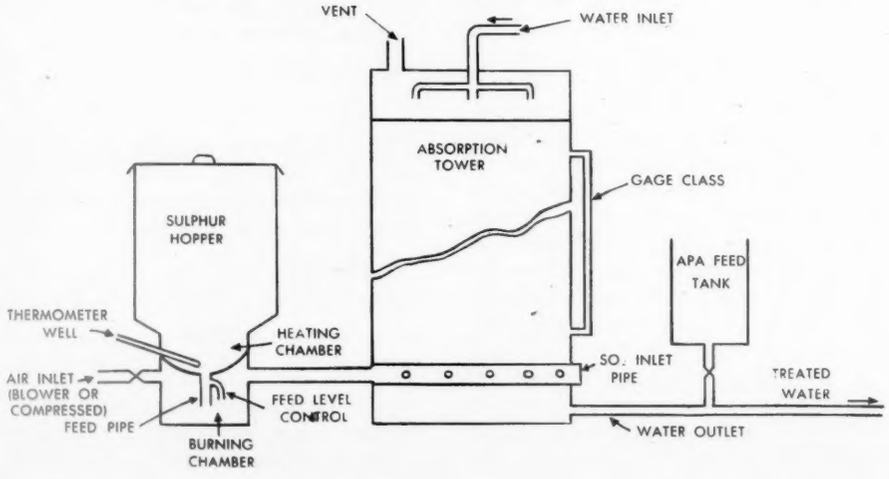
Note; Results are in ppm.

About the same operating conditions were experienced at Plant B. Before the use of the sulphur burner design terminal temperature differences of 5.0 F were exceeded values of 16 to 24 F being common. This condition would often occur in 60 days. Since this tower supplied cooling water for condensers on turbines, it is obvious that a serious decrease in efficiency and capacity resulted. With the burner, in general, design conditions are maintained although values as high as 8 F sometimes occur.

Conclusions

In recent years the chemical and physical aspects of scale and deposit formations and of corrosion in cooling water systems have been fairly well determined. Delignification or deterioration of wood in such systems also is understood. In the cases mentioned, the presence of too much alkalinity, that is a high pH, in the cooling water is the chief cause of the difficulties. In the past, little if anything has been done to correct these situations largely because the acid required is hazardous to use and other acidic materials are too costly. Now owing to the practical application of a sulphur burner and a proper anti-precipitation agent to these problems, a practical solution is possible at little cost and with little maintenance and labor. Proper operation of equipment at high efficiency and capacity and with a minimum of cost and upkeep is thus insured. ★ ★ ★

FIG. 2. Equipment diagram of sulphur burner—APA system for treatment of water to prevent scale and/or lower the alkalinity.



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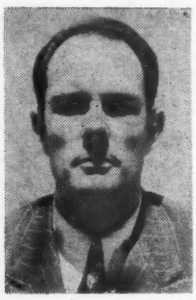
Experience With Odor and Deodorization of Mid-Continent Natural Gas

J. S. POWELL

Mid-Continent gas transmitted to California via the Biggest Inch Pipe Line has a different odor, and its use increased greatly the number of gas leak customer calls to Southern California Gas Company. It was found that addition of air to the gas reduces the quantity of mercaptans present, and increases correspondingly the disulphide content. Air was added to the main line 216 miles from Los Angeles, allowing 24 hours reaction time with the mercaptans in the gas. Complete conversion to disulphides was effected by addition of 0.002 volume per cent of air, about the theoretical amount of oxygen needed for the mercaptan sulphur present. To retain some warning odor, the air was reduced to leave about 0.3 grains of mercaptan sulphur per 100 cu ft of gas. Various methods for sulphur removal are discussed also, herein.

The Author



J. S. Powell is a chemical engineer with the Southern California Gas Company in charge of chemical and engineering laboratory operations. He was graduated from the University of California in 1937 and went to work for the Southern California Gas Company in 1938. During the war, and for a short while afterwards, the Southern California Gas Company operated a Butadiene plant for the Office of Rubber Reserve, Reconstruction Finance Corporation. Mr. Powell was employed in the plant technical department and prior to the close of operations was technical superintendent.

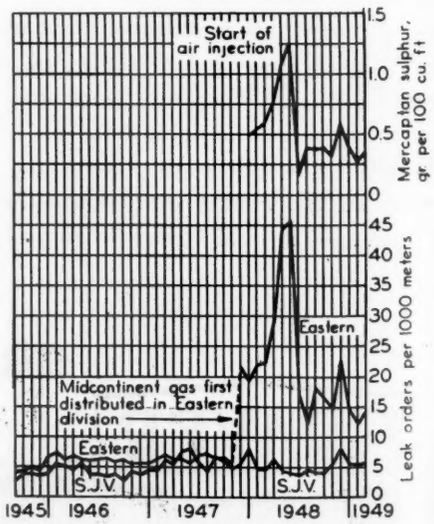
Introduction

NATURAL gas from the fields in Texas and New Mexico was transmitted for the first time in November, 1947, through the Biggest Inch pipe line for distribution in Southern California. A problem resulted because of the difference and intensity of the odor of this Midcontinent gas compared to that of California natural gas previously distributed. The Midcontinent gas after treatment for gasoline, water vapor and hydrogen sulphide removal still contains small concentrations of mercaptans naturally present in the gas. These mercaptans give the gas a strong, penetrating and somewhat unpleasant odor. The California natural gas distributed contains no mercaptans or other sulphur compounds naturally occurring, and the addition of an odorant is necessary. The Southern California Gas Company has been using a commercial odorant for this purpose and its consumers have been accustomed to odorized gas for the past 19 years, associating fuel gas leakage with its characteristic odor. California odorized gas has a neutral odor being neither pleasant nor unpleasant, and its odor is less intense and penetrating than that of Midcontinent gas.

The main concern to the Southern California Gas Company as the result of the distribution of Midcontinent gas, is the fact that there has been a large increase in the number of leak complaints reported by consumers over the previous basic rate, with a subsequent increase in service costs. The leaks reported are in most instances the result of gas discharge from burners previous to the ignition of the gas, or are such small leaks that no hazard is involved. Consequently the service calls are not only more frequent than when California odorized gas was served, but more man hours are spent per investigation, and the public is subjected to unnecessary concern or annoyance. Fig. 1 is a graph showing the leak complaint rate from 1945 through 1948 in the eastern division which has been supplied with undiluted Midcontinent gas since November, 1947; also shown is the leak complaint rate in the San Joaquin Valley where only California natural gas is distributed, as well as the average monthly mercaptan sulphur content of the Midcontinent gas. It will be noted that the leak complaint rate in the eastern division is nearly proportional to the mercaptan suphur content of the gas.

In addition to the odor of Midcontinent gas being a problem, field and laboratory investigations have revealed that the mercaptans present are corrosive to copper and copper bearing alloys and that mercaptans are more corrosive than other types of organic sulphur compounds. This corrosion which results in pilot stoppages, occurs in appliance pilots especially in the copper tubing which supplies gas to the pilot and where the tubing is at an elevated temperature by being in close proximity to the main appliance burner. There is also some evidence that mercaptans in the gas corrode copper even at ambient temperatures. It has been proven that mercaptans will only corrode copper if oxygen is also present in the gas. The Midconti-

FIG. 1. Trend of completed customer leak requests Eastern and San Joaquin Valley divisions and mercaptan sulphur content of Midcontinent gas.



nent gas contains no detectable concentration of oxygen, however in some instances it becomes mixed with California distribution gas, which in most cases contains some oxygen.

An estimate of the increase in service costs attendant with the distribution of Midcontinent gas indicated that it would be economically justifiable to treat it for mercaptan removal. Therefore an investigation herein reported was undertaken to provide a process by which mercaptans in the Midcontinent gas could be either removed, reduced in concentration, or converted to less odorous and corrosive substances.

Sulphur Content of Natural Gas

Midcontinent Gas: Natural gas transmitted through the Texas-California pipe line comes from the Permian basin in West Texas and Southeastern New Mexico and the Hugoton field in the Texas Panhandle. The raw gas from the various sources contains, per 100 standard cu ft, from 30 to 650 grains of hydrogen sulphide sulphur, from 1.5 to approximately 7 grains of mercaptan sulphur and from 0.1 to 0.4 grain of residual organic sulphur.

The gas from all sources is treated to remove hydrogen sulphide and water vapor by passage through glycol-amine plants. The gas from most sources, before treatment in the glycol-amine plants, is also passed through either high or low pressure gasoline absorption plants. From 50 to 85 per cent of the mercaptan sulphur in the gas is removed on passage through the absorption plants, and the residual sulphur is reduced to below 0.1 grain per 100 cu ft. The higher the absorption pressure the more complete is the removal of all organic sulphur.

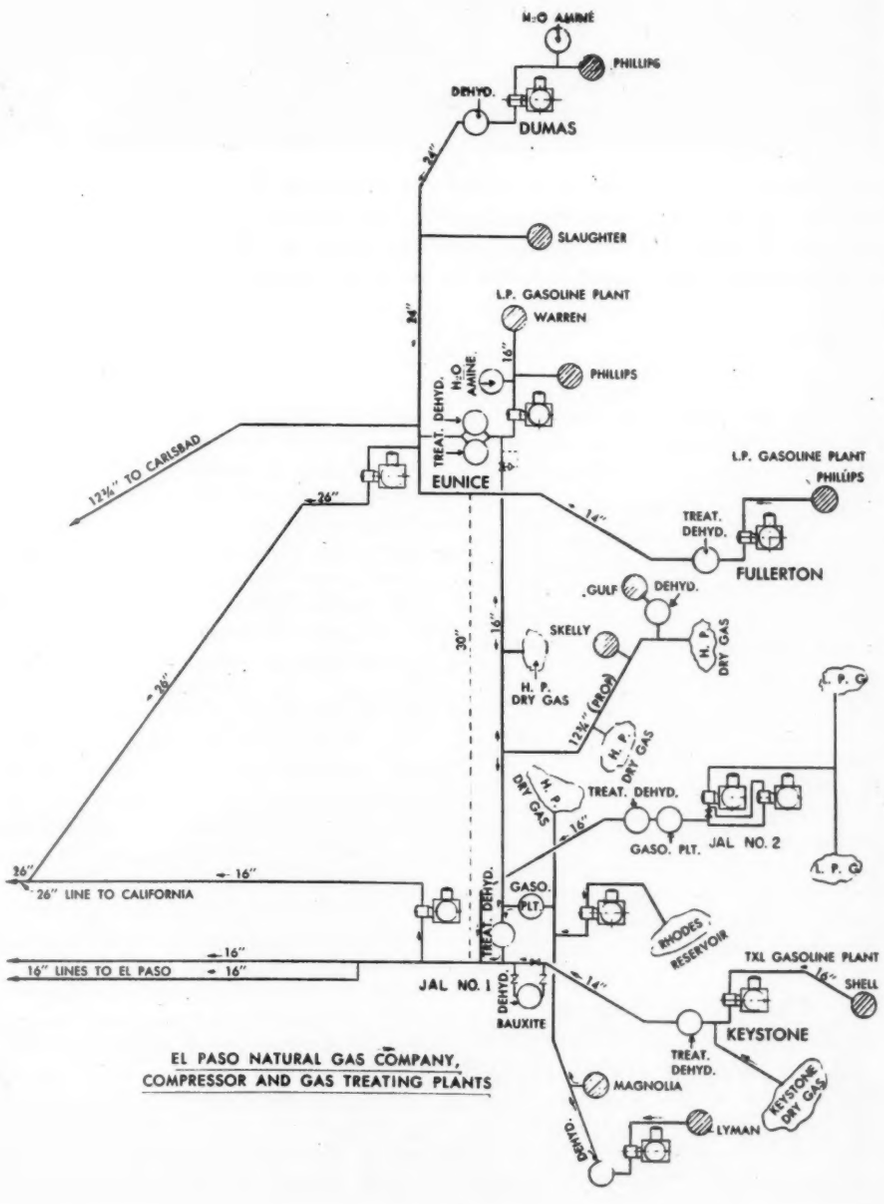
The glycol-amine plants reduce the hydrogen sulphide sulphur content of the gas to below 0.25 grain per 100 cu ft and also take out from 35 to 85 per cent of the remaining mercaptan sulphur. The overall result of the gas treatment is to produce a composite gas from the various sources containing, per 100 standard cu ft, less than 0.25 grain of hydrogen sulphide sulphur, from 0.5 to 1.0 grain of mercaptan sulphur, and less than 0.1 grain of residual organic sulphur. These values may change somewhat due to seasonal changes in plant operating conditions and the percentage change in gas from various sources. During the hot months of the year, the mercaptan content of the gas is higher than during the cold months.

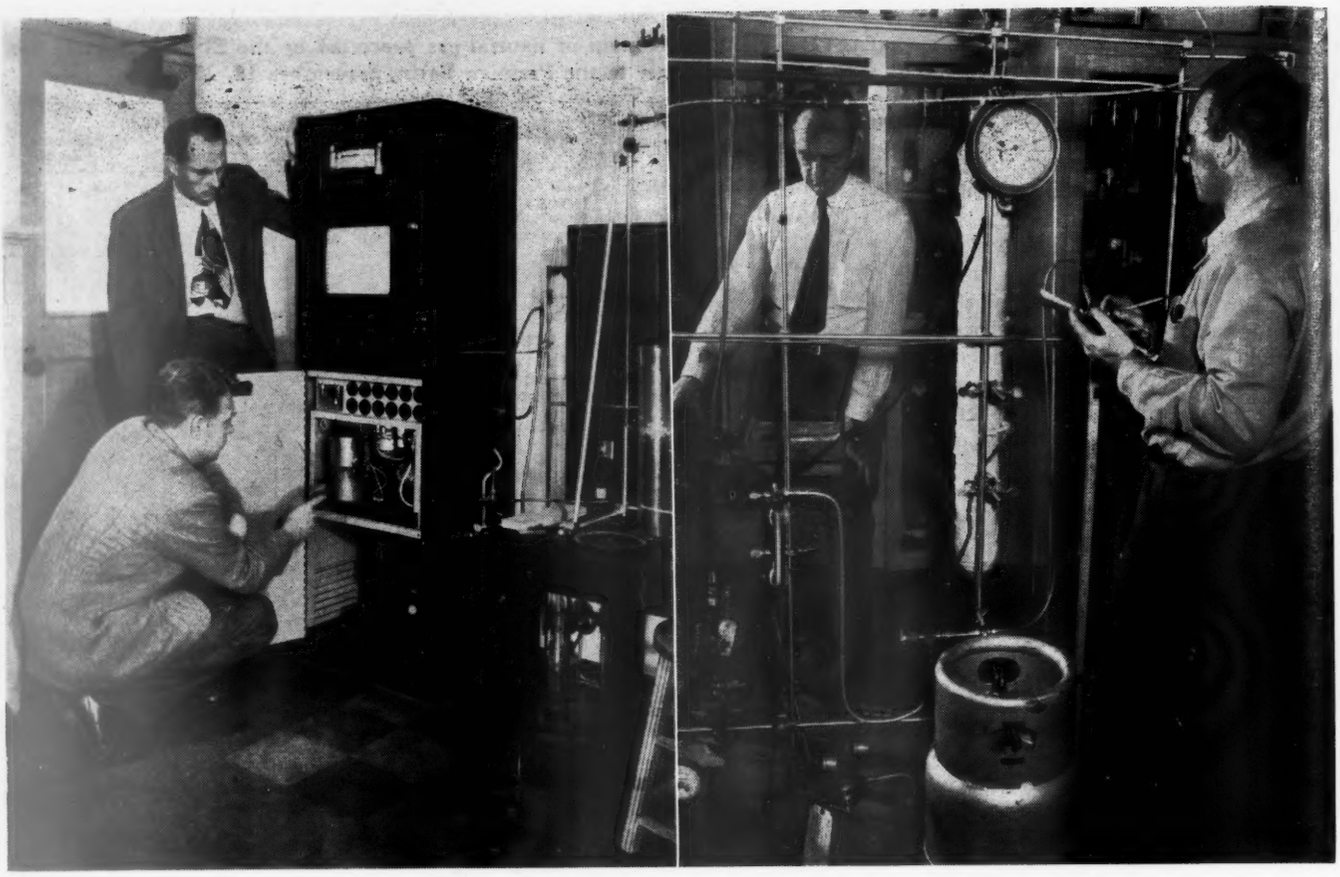
Table 1 gives some typical data on the sulphur content of the gas in and

TABLE 1. Sulphur content of natural gas processed by the El Paso Natural Gas Company in the Permian Basin, September 18, 1947.

Processing plants	Sulphur gr./100 ft³ as; Hydrogen sulphide sulphur	Mercaptan sulphur	Residual sulphur
E.P.N.G. gasoline and treating plant Jal No. I;			
Inlet to high pressure absorption plant (sour gas	136	6.05	0.39
Inlet to high pressure absorption plant (sweet gas	28.6	5.34	0.34
Inlet to high pressure absorption plant (Keystone gas	39.8	1.67	<0.10
Composite gas to treating plant	74.5	0.88	<0.10
Gas from treating plant	None	0.56	<0.10
E.P.N.G. gasoline and treating plant Jal No. II;			
Composite gas to high pressure absorption plant	34.3	3.80	0.10
Gas to treating plant	28.7	1.77	<0.10
Gas from treating plant	None	0.47	<0.10
E.P.N.G. Fullerton compression and treating plant;			
Residue gas to be treated from Phillips low pressure absorption plant	37.0	4.13	0.18
E.P.N.G. Eunice compression and treating plant;			
Inlet to treaters;			
Gas from Warren low pressure absorption plant	611	2.31	
Gas from Phillips low pressure absorption plant	342	3.87	
Gas from treating plant*	2.46	1.35	<0.10

*Plant overloaded not typical of good operation.





J. S. Powell, standing, and F. V. Wilby are examining the Titralog, devised by Consolidated Engineering Company, and used to determine the sulphur content of Texas gas as it flows through the Biggest Inch line at Santa Fe Springs.

Here L. V. Kleiner and Ben Pazol are operating a specially constructed device for the study of sulphur removal from gas by various processes.

out of a few processing plants, and Fig. 2 is a diagrammatic sketch showing the gas sources and plants.

California Gas: The natural gas from the various sources in California distributed by the Southern California Gas Company does not require treatment for removal of sulphur compounds. The gas from all sources contains less than 0.3 grain of hydrogen sulphide sulphur per 100 cu ft, or any gas from a source exceeding this concentration is diluted with other gas to the extent that the mixture is below 0.3 grain. No measurable amount of mercaptan or other organic sulphur is present naturally in the gas distributed. Odorant is added to the gas which introduces about 0.4 grain of organic sulphur per 100 cu ft.

Character of Odor of Midcontinent Gas

The Midcontinent gas received in California for distribution is reported to have an offensive odor and has been described as having an odor similar to cooking cabbage. The odor is essentially produced by the mercaptan sulphur present, and it is believed that this sulphur is mostly methyl mercaptan since the processing operations in Texas would tend to remove preferentially the higher molecular weight mercaptans. The odor of Midcontinent gas can be detected by an individual in a much lower concentration than can California odorized natural gas. However, the individual exposed to the Midcontinent gas odor cannot perceive the odor for as long a time as he can the odor of California odorized gas. It is apparently the nature of the odor of a mercaptan to be detectable in very low concentrations, but also to rapidly fatigue the olfactory senses. The odorant used in odorizing California natural gas is a mixture of various organic sulphur compounds essentially of the sulphide and disulphide type. It appears from recent studies that the threshold concentration of this type of odorant for odor detection is not as low as that of the mercaptan type of odorant, but it is more persistent on continuous exposure.

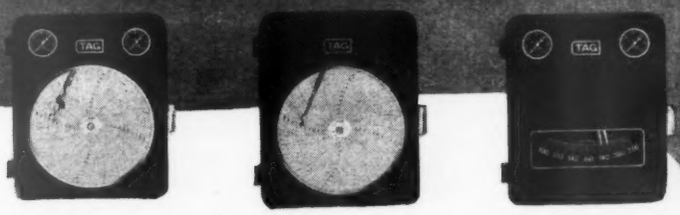
The nature and concentration of mercaptans in Midcontinent gas make possible the detection of leakage gas in a dwelling in very small concentrations, especially on first exposure to the odor. Such leakage might result from the delayed ignition of a burner or from very small leaks in gas piping systems. The concentration of gas detectable is far below that which would constitute a hazard.

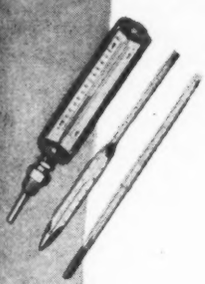
Chemical Nature of Mercaptans

There is a homologous series of mercaptans similar to that of the saturated hydrocarbons. Some of the first members of this family in the order of their increasing molecular weight and boiling points are methyl mercaptan, ethyl mercaptan, propyl mercaptan, butyl mercaptan and amyl mercaptan. The chemical formula of a mercaptan is RSH where R designates the parent hydrocarbon or alkyl group.

The mercaptans are among the most odorous compounds known, all having unpleasant odors. The lowest molecular weight mercaptans have the most offensive odor and the odor of the mer-

TAG Instruments





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Viscosimeters
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Indicating Controllers
Recording Controllers
Recorders—Single and Multiple Point

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Motion
Pressure
Temperature
Vacuum

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Hydrogen Ion
Pressure
Temperature
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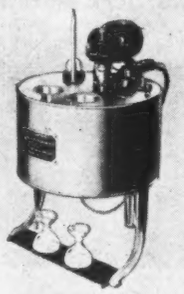

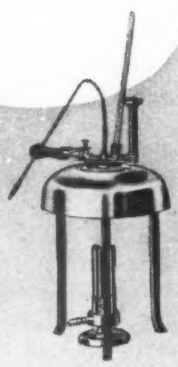

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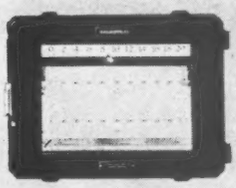

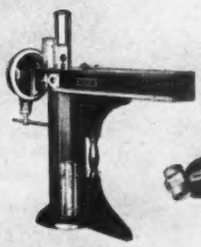

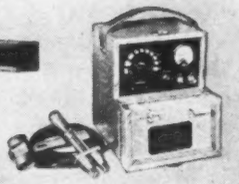

C. J. TAGLIABUE CORPORATION (N. J.)

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TAG

captan becomes less offensive as the molecular weight increases.

Mercaptans are quite chemically reactive and therefore are not very stable. The two most common reactions which they undergo are (1) reaction with a strong base or heavy metal salts to form mercaptides, and (2) oxidation to form disulphides or higher oxidation products. For example sodium hydroxide solution absorbs mercaptans to form soluble sodium mercaptides, a silver nitrate solution will absorb mercaptans to form insoluble silver mercaptides, and oxygen in the presence of a catalyst will readily oxidize mercaptans to disulphides.

Disulphides have the formula R-S-S-R, and nearly double the molecular weight of the mercaptan from which they are formed. Consequently they have a much higher boiling point than the corresponding mercaptans. Also the odor of the disulphides is much less unpleasant and less intense than that of the parent mercaptans.

First Attempt at Gas Odor Control

Laboratory tests showed that when air was added to Midcontinent gas confined and circulated in a closed vessel, consisting of two parallel lengths of 26-in. pipe connected together at each end, the mercaptan concentration of the gas rapidly decreased with an increase in the concentration of disulphides. When all of the mercaptans had been converted, the gas was almost odorless. As the result of this experimental work, air was injected into the Texas-California pipe line early in June, 1948, at Blythe, California, which is 216 miles from Los Angeles, providing a reaction contact time of approximately 24 hours. Complete conversion of the mercaptans in the gas to disulphides occurred within the first 100 miles of pipe line. The quantity of air required for complete conversion of the mercaptans was approximately the amount necessary to supply the theoretical amount of oxygen or 40 cu ft of air per MMCF of gas per grain of mercaptan sulphur. The Midcontinent gas at this time which contained about 0.5 grain of mercaptan per 100 cu ft required the addition of 0.002 volume per cent of air to produce complete conversion of the mercaptans.

Complete conversion of the mercaptans in the gas was not desired since the odor of the gas was so slight under such conditions that odorization would have been necessary. Therefore the air injection rate was adjusted to maintain the mercaptan level of the gas at about 0.3 grain of mercaptan sulphur per 100 cu ft. In this manner the mercaptan sulphur level was controlled for several months, however, it was observed that the length of pipe line required for conversion of the mercaptans gradually increased with time, until eventually no significant conversion occurred in the pipe line between Blythe and Los Angeles, regardless of the quantity of air added.

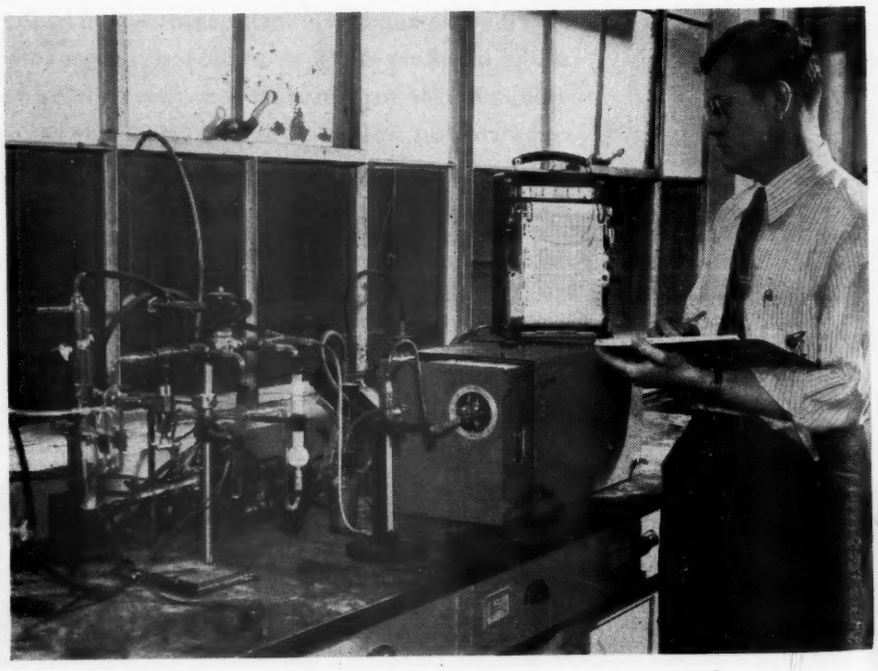
The injection of air into the pipe line at Blythe immediately resulted in a decrease in the number of leak complaints as is shown in Fig. 1, and although the ability of the air to oxidize the mercaptans in the gas decreased with time, the mercaptan content of the gas remained quite low because additional gas was obtained from other sources in Texas of lower sulphur content and more efficient treatment of the gas in the processing plants occurred due to seasonal changes in conditions.

The conditions for the oxidation of mercaptans to disulphides by oxygen were further studied in the laboratory. It was learned that oxygen alone would not oxidize mercaptans, but would only do so in the presence of iron oxide. The iron oxide had to be in an active form. Ignited iron oxide was not active but an active type was that obtained from iron rusting in the atmosphere. However, iron oxide did not permanently retain its activity in promoting the oxidation of mercaptans. On use it gradually became less active until the oxidation of mercaptans by oxygen in its presence no longer took place. Comparative chemical analyses of inactive iron oxide and the active form did not reveal any apparently significant differences in composition. The inactive iron oxide only contained approximately 0.4 weight per cent more sulphur than the active type and both materials had about the same ratio of ferrous to ferric iron.

The oxidation of various types of mercaptans as contained in the commercial odorants of the mercaptan type was investigated. It was found that all mercaptans from methyl through amyl mercaptan were readily oxidized at about the same rate by oxygen in the presence of iron oxide. Thus it can be seen, that the mercaptan type of odorants on first use would not be stable in pipe line systems containing gas with oxygen present. However, it would be expected that with the continual use of such odorants they could become stable when the iron oxide on the walls of the pipe lines became inactive.

Apparently the oxidation of mercaptans to disulphides in one part of a pipe line system and then subsequent reduction of these disulphides back to mercaptans in another part of the system is possible. Such a phenome-

Mercaptans, especially objectionable from the standpoint of odor, are converted by this apparatus to less odorous compounds. Jack Mazelli is the research assistant making notes.



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Patent No. 2,117,175

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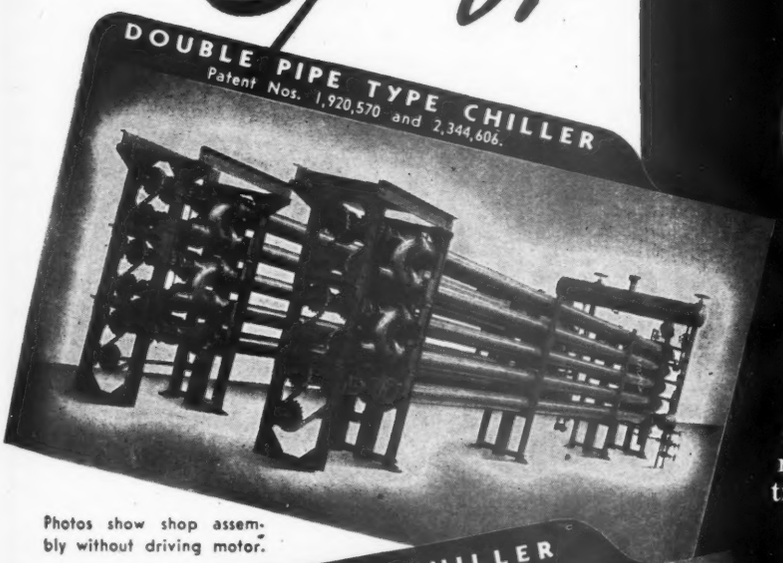
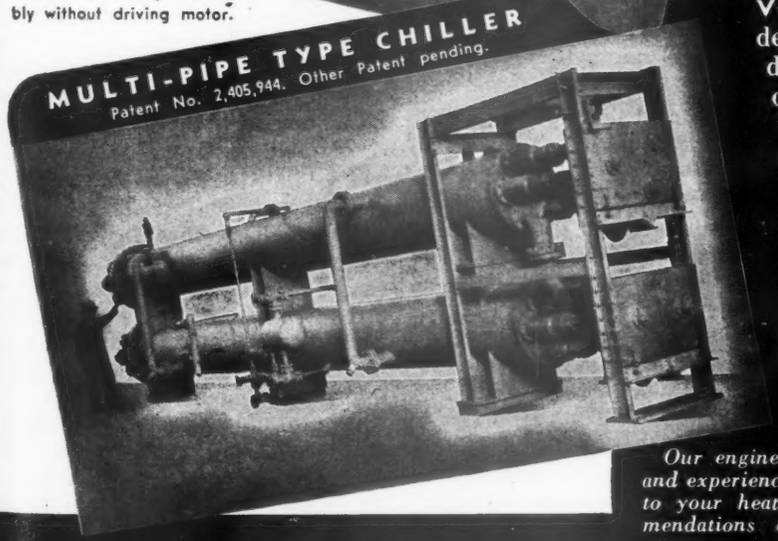


Photos show shop assembly without driving motor.



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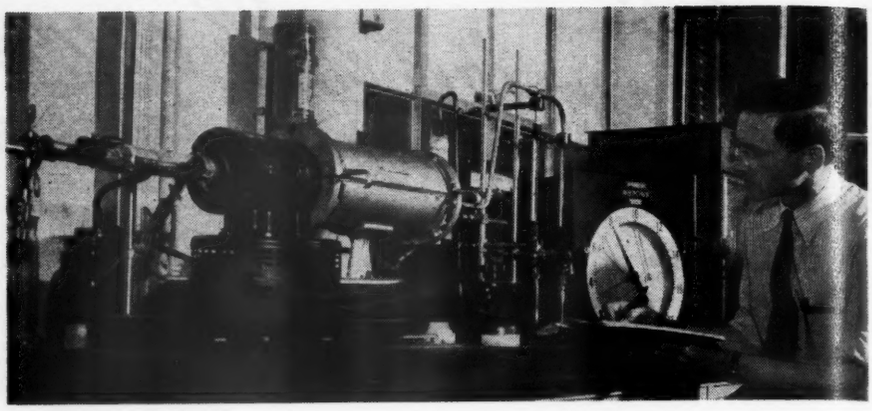
non occurred in the offtake line from the main California-Texas pipe line to supply gas to the Imperial Valley. This pipe line consists of about 80 miles of 8-in. pipe from the off-take point to Calipatria, California. From Calipatria to the Mexican border various sizes of pipe were laid. The 8-in. line was laid with new pipe whereas the remainder of the line was laid with reclaimed pipe. When Mid-Continent gas containing a small amount of oxygen was first passed through this line, complete conversion of the mercaptans to disulphides occurred by the time the gas reached Calipatria. However, further tests of the gas for its mercaptan content downstream from Calipatria revealed that there was a gradual increase in the mercaptan content of the gas along the pipe line, reaching a maximum of about 0.4 grain per 100 cu ft at the southernmost part at Calexico.

The only apparent logical explanation of this phenomenon is that the reclaimed pipe downstream from Calipatria afforded a reducing environment because of the nature of its surface, causing the disulphides formed in the first part of the line to be reduced back to mercaptans. That such a reduction did take place was confirmed by chemical analyses of the gas along the pipe line at several different times for both mercaptan and total sulphur. Futhermore it was shown in the laboratory that iron wet with slightly acid water would readily reduce disulphides in gas to mercaptans.

Processes for Mercaptan Sulphur Removal or Conversion

When it was apparent that the injection of air into the California-Texas pipe line would not permanently bring about the conversion of the mercaptans in the gas to disulphides, laboratory work on the development of a plant process to adequately treat the Mid-Continent gas to effect odor removal was undertaken. Two types of processes are being considered: (1) complete sulphur removal, and (2) conversion of the mercaptans to disulphides. The former would be the most satisfactory since after reodorization of the treated gas from both types of processes with a sulphur containing odorant, the total sulphur content of the gas treated by the former process would be lower than when treated by the latter. A low sulphur content of the gas is desirable since it has been shown that sulphur compounds in gas assist in corroding pilot tubes and tips forming corrosion products resulting in pilot stoppages.



Excess of organic sulphur compounds in gas for domestic use causes fouling and eventual stoppage of pilots. Myron L. Robinson is here in charge of a set-up that measures this effect in relative terms.

Removal Processes: Removal processes fall into three classes:

(1) The use of a liquid or solid material which is brought in contact with the gas and removes the mercaptans present by chemical combination, (2) catalytic conversion of the sulphur compounds in the gas to hydrogen sulphide with the subsequent removal of the hydrogen sulphide, and (3) the use of a solid or liquid brought in contact with the gas which removes all sulphur compounds by physical absorption or adsorption.

Processes which have been investigated or considered of the type described in (1) are listed below:

a. Scrubbing of the gas with caustic solution,
b. Scrubbing of the gas with solutions of zinc or cadmium salts,
c. Scrubbing of the gas with solutions of calcium hypochlorite or sodium hypochlorite,
d. Contacting of the gas with copper oxide placed on a suitable solid carrier.

All of the above processes employing water solutions of a reagent have a big disadvantage in that the gas would be rehydrated and would require subsequent dehydration. In addition processes a and b are not economical if the gas contains carbon dioxide above 0.005 per cent which is quite likely possible. Process d has the disadvantage that in order for the mercaptans in the gas to react with copper oxide, the gas must have a higher dew point than desirable. Also this process gives both removal and conversion.

There is only one process of the type described in (2) which has been investigated; this is the catalytic conversion of the sulphur compounds in the gas to hydrogen sulphide by bringing the gas at a temperature of about 700 F in contact with a solid carrier impregnated with compounds of cobalt and molybdenum. This process has many disadvantages in that high temperatures are required, incomplete conversion is obtained, and the removal of the hydrogen sulphide would be a costly operation.

Process of the type described in (3) which have been considered or investigated, or are being investigated, are as follows:

a. Scrubbing of the gas with absorption oil,
b. Passing the gas through a bed of activated charcoal,
c. Passing the gas through a bed of silica gel.

Process a has been eliminated because calculations have shown that an absorption oil process would not be practical to remove such small concentrations of low molecular weight mercaptans.

Process b is now being thoroughly investigated. This process would be satisfactory, if the capacity of the charcoal to remove sulphur compounds from the gas would not decrease significantly on continuous use involving a cycle of adsorption and reactivation. So far in a laboratory test simulating the conditions for a plant operation, the charcoal suffers a large drop in capacity after a few cycles of adsorption and reactivation. This change in capacity may be due to compressor oil in the gas from the laboratory compressor being adsorbed by the charcoal and not displaced during reactivation. If such is the case, a plant process may still not be feasible since the pipe line gas is passed through absorption oil plants, oil-type

dust scrubbers, and compressor plants providing ample opportunity for the gas to pick up oil. Further work is necessary before a definite conclusion can be reached.

The use of silica gel as an adsorbent to remove sulphur compounds from the gas is also being studied. Silica gel has a greater affinity for organic sulphur compounds than for hydrocarbons, and consequently it has been found to adsorb mercaptans and residual organic sulphur from the Mid-Continent gas without reducing the heating value of the gas, as much as occurs with activated charcoal. Furthermore, no loss in capacity of the silica gel appears to take place after numerous cycles of absorption and reactivation.

Conversion Processes: The conversion processes investigated or being investigated are of two types: (1) the oxidation in situ of mercaptans in the gas to disulphides by the injection into the pipe line of an oxidizing agent not requiring the presence of a catalyst to promote the oxidation, and (2) the oxidation of the mercaptans in the gas to disulphides by injecting air into the gas prior to the passage of the gas through towers packed with a catalytically active material to promote the oxidation. Examples of the first type which have been investigated are:

a. Oxidation with ozone.
b. Oxidation with chlorine.
c. Oxidation with nitrogen dioxide.

Preliminary tests have indicated that ozone will oxidize the mercaptans in the gas. Apparently the oxidation goes beyond the disulphide stage. The results of these tests have been sufficiently encouraging that the economics of such a process will be studied, and if they are favorable, more laboratory work will be performed to determine the best operating conditions and the nature of the oxidation products formed.

It has been found that chlorine does not oxidize the mercaptans in the gas to disulphides but apparently forms a substitution product that has an odor of a rather irritating nature. Because of this, and the possibility of internal pipe line corrosion if chlorine were injected into the gas, Process b has been eliminated.

Process c has been eliminated since it has been found that there is no reaction between nitrogen dioxide and mercaptans under the conditions that would be imposed.

A plant process using air and a catalyst to promote the oxidation of the mercaptans in the gas to disulphides, is being developed at present. Laboratory work has revealed that there are a number of catalytic substances which will promote at ambient temperature the oxidation by oxygen of mercaptans to disulphides. The most active of these are the oxide of cobalt and iron. Suitable catalytic material has been prepared by soaking pumice granules in a strong solution of either cobaltous or ferric nitrate, and then decomposing the nitrate to the oxide by heating the pumice granules to 600 F in the presence of steam. On use the catalyst gradually loses its activity and eventually requires reactivation. It has been found that reactivation can be accomplished by passing a mixture of steam and air through the catalyst bed at 400 F for several hours.

Summary

The residual mercaptan sulphur in Mid-Continent gas gives it a stronger and more unpleasant odor than that of California odorized natural gas. This has resulted in a higher leak complaint rate in the areas served with Mid-Continent gas than formerly existed when California gas was served. The leak complaint rate and mercaptan content of the Mid-Continent gas correlate well.

The mercaptan content of the Mid-Continent gas was successfully reduced temporarily by the injection of air into the Texas-California pipe line, thus causing the conversion of mercaptans to disulphides. The iron oxide on the pipe wall acted as a catalyst in this oxidation process, however, after several months it became inactive and the oxidation ceased.

Work is presently in progress to develop a reliable and economic process by which mercaptans and other sulphur compounds can be removed from the Mid-Continent gas or, as a less desirable alternative, a process for the conversion of mercaptans to disulphides. A process of the former type which is under investigation is to contact the gas with an adsorbent such as activated charcoal or silica gel. Work on this process is still in the laboratory stage and has not yet been successfully completed. A process of the latter type on which laboratory scale work is nearing a successful completion, but would of course have to be proved by pilot plant operation, is the oxidation of mercaptans to disulphides with air in the presence of an iron oxide or cobalt oxide catalyst. A means of reactivation of these catalysts after they have become inactive has been found which promises to make such a process practical in a plant type of operation.

* * *

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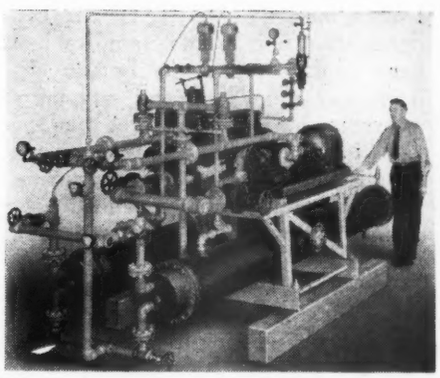

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Progress Report on Low Temperature Fractional Analysis Project for Liquid Hydrocarbons*

A. J. MILLER†

Low temperature fractional analysis is a tool of fundamental importance to the natural gasoline and other branches of the petroleum industry. Basic information for plant design, operation, efficiency tests, product specifications, accounting procedures, and other purposes is often dependent upon the reports from the fractional analysis laboratories.

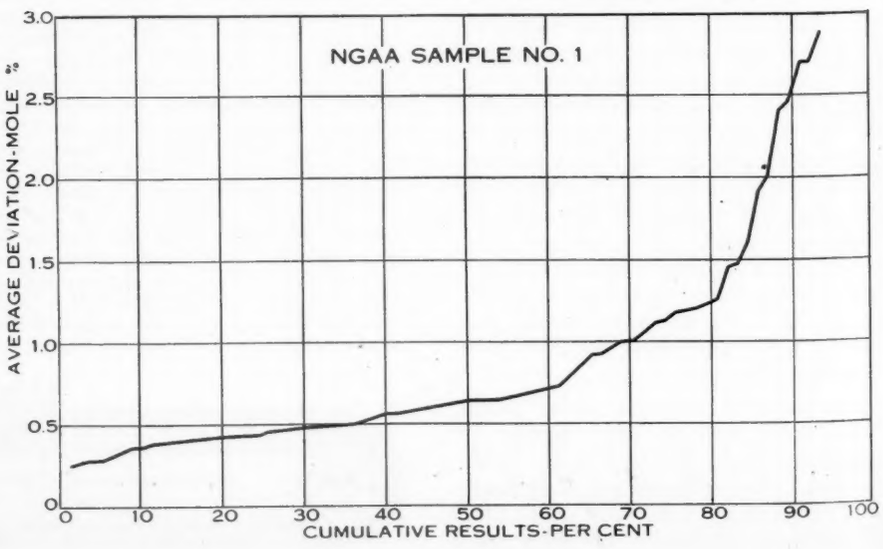
Although there is general agreement as to the importance of this analytical method, the same cannot be said as to the techniques and equipment involved, nor to the resultant accuracies that may be expected. In recognition of this, the NGAA initiated about 10 years ago, a series of studies designed to obtain information relative to the duplicability of fractional analyses among different laboratories, and to improve this duplicability by fostering a rigorous attention to the details of good analytical technique. Eighteen laboratories analyzed identical gas samples from a master holder. It became evident, after five master samples had been analyzed, that the human element was a much greater and more unpredictable source of error than the variations in equipment that existed among the cooperating laboratories. Then, a tentative recommended procedure was used by the cooperating laboratories in analyzing a second set of four master samples, the results of which, compared with the results of the first set of samples, proved that human errors had been materially reduced and duplicability between laboratories improved, all without requiring fixed adherence to standardized equipment. Mr. Howard Montgomery, who was chairman of the gas fractional analysis committee, has concisely described to you the progress of this program in NGAA Convention reports in 1941, 1942, and 1943. Resulting from this program was the NGAA Publication 1146, entitled "Recommended Procedure for Analysis of Saturated Hydrocarbon Gases by Low Temperature Fractional Distillation."

Liquid Fractional Analysis Program

Now, the NGAA is taking another step to evaluate and possibly improve the accuracy of low temperature fractional analysis by sponsoring a similar program using a group of liquid hydrocarbon samples, the compositions of which are known by synthesis. In this program it will be possible to evaluate the accuracy of the results instead of just the deviation from the mean, as was the case in the gas analysis program. Three types of liquid samples were chosen for this program: (1) A propane-butanes LPG mixture with possible light and heavy end contaminants; (2) a butanes mixture with possible light and heavy end contaminants; and (3) a mixed pentanes sample with possible light and heavy end contaminants. The chemical products department of Phillips Petroleum Company blended these samples from hydrocarbons of 99 mole per cent minimum purities. The impurities in each component were known and taken into account in calculating the compositions of the blends. The accuracy of all components in the blends is considered to be within ± .05 weight per cent of the total sample.

The first hydrocarbon mixture was shipped to 58 participating laboratories, representing 35 oil companies and 5 commercial laboratories. It is unfortunate that about a dozen of these laboratories did not mail their results in time to be included in the preliminary correlation of results herein presented. However, all of the results received will be tabulated and mailed to all participating laboratories together with a compilation of the answers to the questionnaire that each laboratory filled in when reporting the analytical results. Thus, each laboratory will be able to compare its results and details of technique and equipment with all the others. The tabulations are coded so that the results and data cannot be identified except by a laboratory's own personnel. This complete compilation will be mailed as quickly as possible and then the analysis of the second hydrocarbon mixture will begin.

FIG. 1. Average deviation of all components from true value.



*Liquid Fractional Analysis Program has been conducted by the Natural Gasoline Association of America Fractional Analysis Committee.

†Phillips Petroleum Company.

N.B. While it is axiomatic that return on investment—the *ultimate earning* power of a refinery unit when actually on stream—is the only true evaluation of competitive engineering recommendations, initial plant costs remain a major factor in refiners' decisions on plant installations. M. W. Kellogg takes specific steps to *minimize initial plant costs* consistent with the achievement of *highest ultimate earning power.*

A THREE-WAY PIPE STORY!

Consider for a moment that piping accounts for about one quarter of the cost of the average installation.

That can put piping in the million and often multi-million dollar class. If savings of from 10 to 20% can be effected, refiners will realize important economies, particularly attractive in these days of high costs.

Of course, accurately computing specific savings on a piping job is virtually impossible. There are too many variables. But Kellogg today estimates that its methods of field fabricating lop upwards of 15% off the cost of refinery piping work.

Here's why.

First, pipe is bent on the site as needed. No waiting for key pieces to arrive. Even one day saved over the course of the entire job represents a sizable sum both in labor savings and in the refiner's operating revenue.

Second, the shop overhead of the plant where such pipe would normally be fabricated, is dispensed with entirely.

Third, Kellogg's own crews handle the piping fabrication in the field, hiring necessary supplementary craft labor on an hourly basis. Thus there are no sub-contractors' fees pyramiding on the cost of the job.

There are still other advantages such as savings in shipping straight pipe rather than space-consuming, odd shapes, and they all add up to money in the bank for the owner.

Kellogg's development of field fabricating techniques sounds rather obvious and certainly simple when explained this way—but it wasn't. The move required that shop equipment be duplicated in mobile form, that shop techniques and quality standards be duplicated under field conditions subject to both the weather and the physical idiosyncracies of each job site.

Such an operation as this is only possible when backed, organized and controlled by a *complete* organization—such as that of M. W. Kellogg—where all types of specialists are available for handling the myriad problems involved. These savings effected in field fabrication of piping provide further proof that *completeness and integration of the engineer-contractor* are the keys to LOW INITIAL PLANT COST.

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A SUBSIDIARY OF PULLMAN, INC.
ENGINEERS TO THE PETROLEUM INDUSTRY

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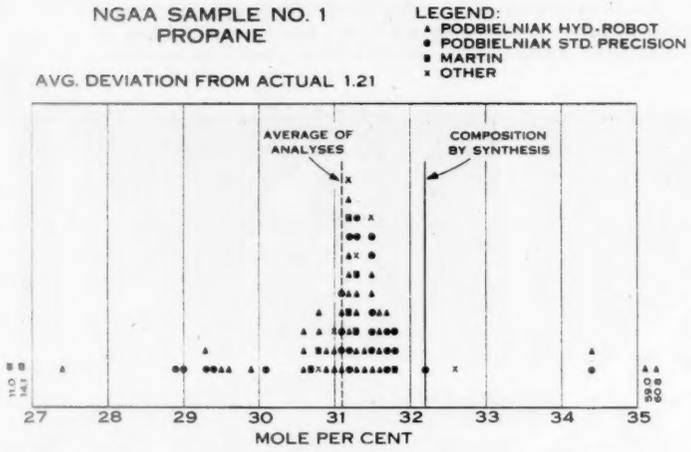


FIG. 2. Frequency distribution plot 0.1 Mol per cent interval.

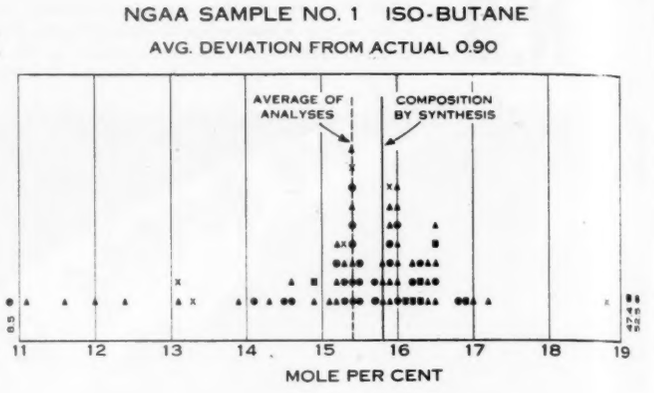

NGAA SAMPLE NO. 1 ISO-BUTANE
AVG. DEVIATION FROM ACTUAL 0.90
AVERAGE OF ANALYSES
COMPOSITION BY SYNTHESIS
11 12 13 14 15 16 17 18 19
MOLE PER CENT

FIG. 3. Frequency distribution plot 0.1 Mol per cent interval.

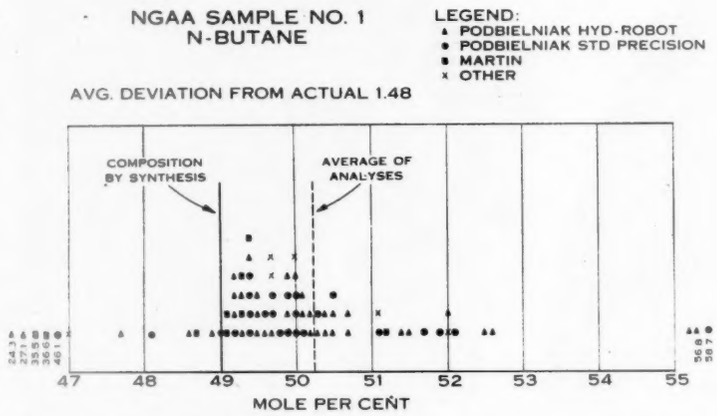


FIG. 4. Frequency distribution plot 0.1 Mol per cent interval.

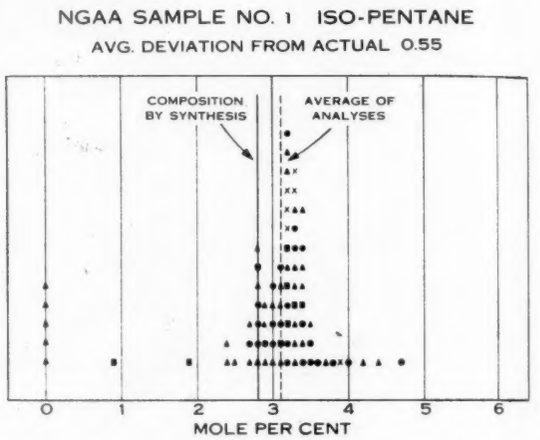

NGAA SAMPLE NO. 1 ISO-PENTANE
AVG. DEVIATION FROM ACTUAL 0.55
COMPOSITION BY SYNTHESIS
AVERAGE OF ANALYSES
0 1 2 3 4 5 6
MOLE PER CENT

FIG. 5. Frequency distribution plot 0.1 Mol per cent interval.

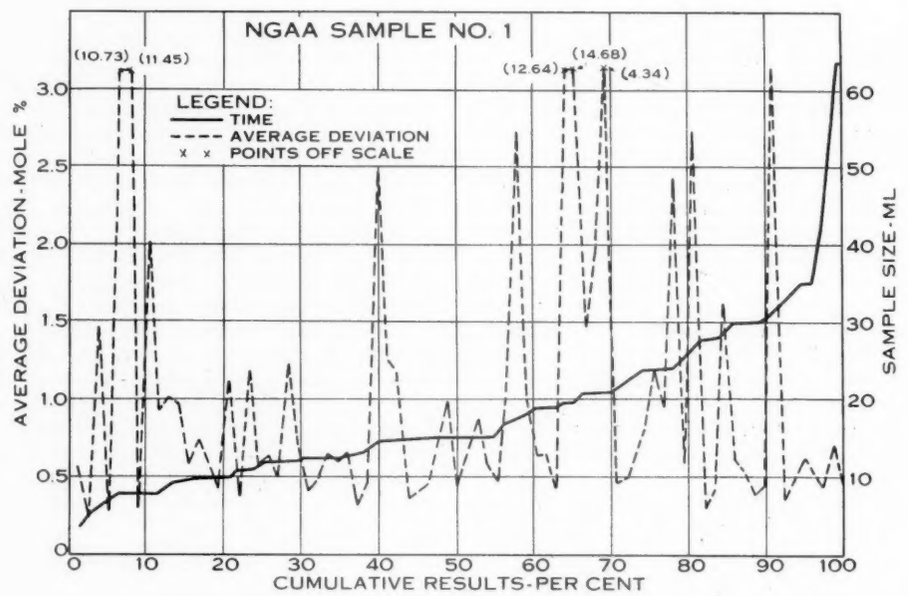


FIG. 6. Size of sample and average deviation.

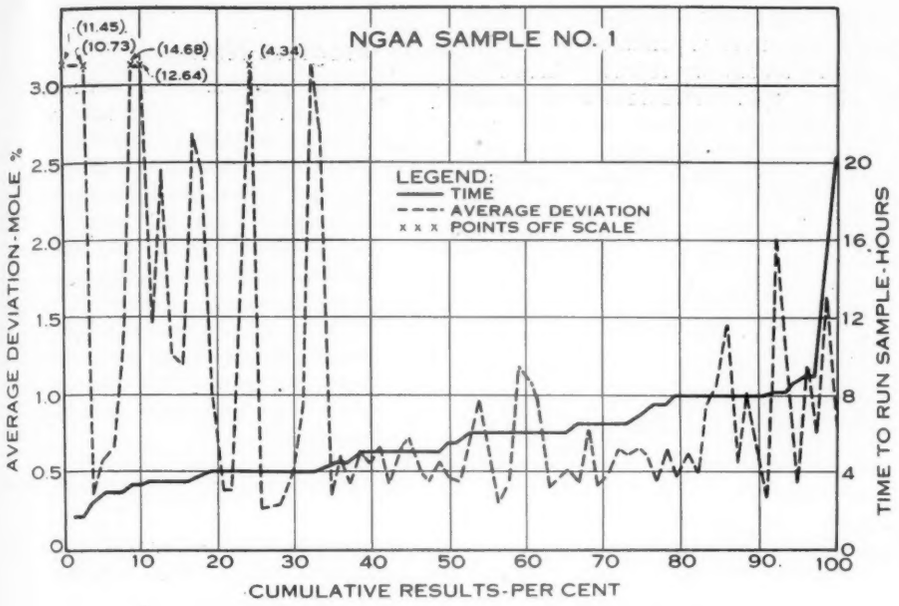


FIG. 7. Time to run sample and average deviation.

The deviations for the individual components are shown by frequency distribution plots in Fig. 2, 3, 4, and 5. The deviations from the synthesis composition for the individual components were averaged as follows:

Component	Avg. deviation
Propane	1.21
Iso-butane	0.90
N-butane	1.48
Iso-pentane	0.55

The quantity of n-pentanes in the sample was too minute to warrant computation of its average deviation.

Fig. 6, 7, and 8 present plots of the average deviations of the results against the factors of sample size, analysis time, and gas receiver size, respectively. The sample size ranged from 3.5 ml to 100 ml while the analysis time ranged from 1¾ to 20 hours. It is indicated, that for this type of liquid blend, a sample size of 5 to 10 ml is sufficient, and that there is no apparent advantage in taking longer than four to eight hours to make the analysis.

A mass of data and many details of technique were submitted with the reports, which will require much study and comparisons with results on more types of samples before any recommendations are warranted. Many of the laboratories submitted comparative analyses using differences in technique or equipment. Typical of this is a laboratory that submitted two analysis reports with this comment:

"In as much as the large majority of our samples do contain appreciable

Results Obtained on the First Liquid Sample

Convention time this year is a little early for a complete report on the results of the first sample as a number of the laboratories registered rather late, and the results were trickling in daily as this correlation was being prepared. In order to include as many results as possible, preparation of this correlation was delayed to the last minute, when 80 results had been reported by 47 laboratories. The arithmetical average of these results, omitting four results from two laboratories that were greatly out of line, is compared with the synthesis composition in Table I. Also shown as a matter of interest is the closest result to the synthesis composition.

As low and high values tend to compensate, the arithmetic average of the results is not too significant and a more comprehensive evaluation of the accuracy of the results is depicted in Fig. 1, which plots the average deviation for each analysis arranged in increasing order. Approximately 30 per cent of the results are within an average deviation of 0.5 per cent, while 70 per cent are within 1.0 per cent, and nearly 95 per cent are within 3.0 per cent. Only five results showed an average deviation greater than 3.0 per cent and these ranged from 4.34 per cent to 14.68 per cent.

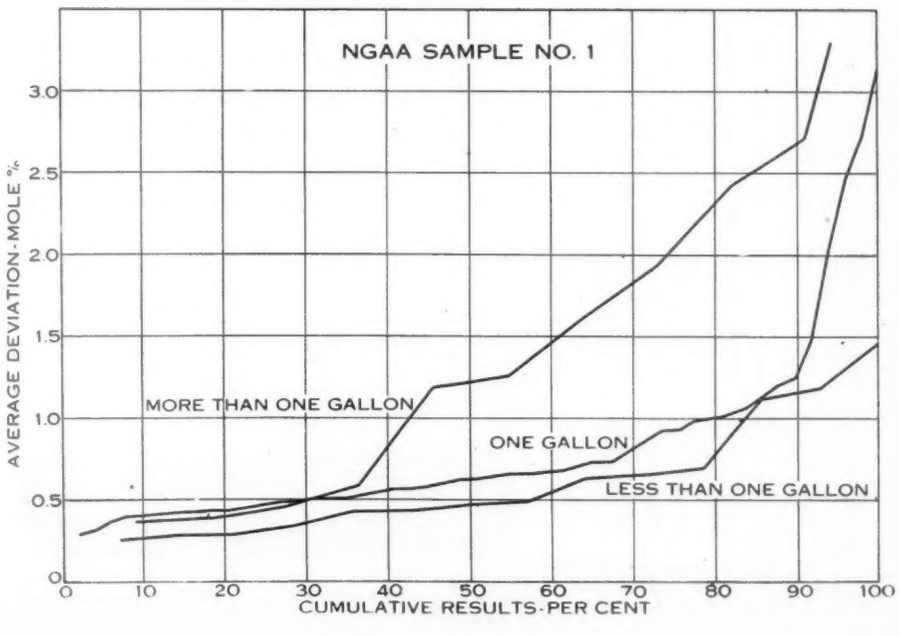
TABLE 1. Data from 76 results on NGAA. Sample No. 1.

Component	Composition by synthesis	Average Result	Best result	
	Mole %	Mole %	Mole %	Deviation
Propane	32.19	31.13	32.067	−.123
Iso-butane	15.81	15.38	15.687	−.123
N-butane	48.99	50.23	49.207	+.217
Iso-pentane	2.77	3.08	3.039	+.269
N-pentane	0.24	.18*		−.24
Total	100.00	100.00	100.000	0.972
Avg. Deviation				.194

*Avg. of n-pentanes plus as reported for all samples including 58 results with zero value. The average for the 18 actual n-pentane values reported was 0.77 mole %.

2 Results showed 0.11 mole % methane
5 Results showed from 0.04 to 0.09 mole % ethane
18 Results showed n-pentane
8 Results showed from 0.14 to 1.05 mole % hexanes

FIG. 8. Average deviation vs size of gas measurement bottles.



quantities of normal pentanes and heavier, we do not often employ a 'chaser.' Run number one was made using our normal procedure. Run number two was made in the same manner as run number one except that a chaser, high purity iso-octane, was added."

In this case 0.55 mole per cent of normal pentane was reported for the run without "chaser," while no normal pentane was reported for the run using a "chaser." The synthesis value for this component was 0.24 mole per cent. Another laboratory that reported results using a "chaser" obtained very close agreement with the synthesis value for normal pentanes.

One laboratory reported three runs using vapor pressure measurements on the cuts between plateaus, and all results were less than 0.3 per cent average deviation. These three runs were made by different analysts, and considering all results submitted by the laboratories, this was the most accurate set received.

Conclusions

The results reported on the first liquid hydrocarbon blend show much less deviation than the results obtained on the gas samples analyzed in the earlier NGAA fractional analysis program. This may be due in part to differences in the type of samples but does indicate that progress in low temperature fractional analysis has been made. The data obtained on this type sample should not be generalized to interpret accuracies that may be expected on other type samples such as analyses on field gases to determine their gasoline contents because of the quantity differences of the components involved.

The conclusion made in the past gas analysis program that exact equipment standardization is not as important as "human element" factors, is again indicated, as good results were obtained with various types of equipment while there were other cases of proper results on the same types of apparatus. Some important "human element" factors include clean and leak-free equipment, careful attention to obtaining correct readings, correct calibrations, and the like.

The gratifying response of laboratories to participate in this program and their excellent cooperation in presenting details, comments, and comparative data reflects a genuine interest on the part of the analysts themselves to improve the accuracy of low temperature fractional analysis, and insures that progress towards this end will continue.

Acknowledgment

The liquid fractional analysis program has been conducted by the NGAA Fractional Analysis Committee, the other members of which are G. T. Hamblen of Continental Oil Company, I. L. Malm of Cities Service Oil Company, and Joe Wood of Skelly Oil Company. In addition, D. E. Smith and H. E. Shobe of Phillips Petroleum Company have rendered significant assistance to the committee.

* * *

Progress Note

Many of the small roadside service stations, which sold as little as 500 gal of gasoline a week and were closed during the war years, are blossoming out again. They are popping up in many places, and suppliers are loaning them equipment to get a fresh start in life. These small service stations are perfect examples of the independent competition that has made the petroleum industry progressive.

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Propane Recovery by Absorption*

By LUDWIG KNIEL†

Increased Recovery of Propane. When it is desired to increase propane recovery in an existing absorption plant one of the first measures taken may be the substitution of a lower molecular weight absorption oil which may or may not have the same volatility characteristics. The next step would be concerned with measures to increase the lean oil circulation or, if this course should not be feasible, with efforts to lower the absorber temperature. Substituting a lower molecular weight lean oil of the same characterization factor, that is of correspondingly greater volatility, will increase the lean oil loss over the absorber; if an oil having a lower characterization factor but the same volatility is used it will probably be found to be less stable and to result in a greater loss of heavy ends over the rerun still. It is then up to the operator to determine where his greatest gain lies. Adequate increases of the lean oil rate often require modifications or additions to existing equipment and the lowering of the absorber temperature beyond that obtainable with additional lean oil coolers is definitely a major operation.

All of these measures to increase recovery are eventually limited by the capacity of a particular plant to handle and to eliminate efficiently the larger volumes of ethane and methane which attend the removal of an increased proportion of the propane with the lean oil. The objective obviously is to obtain the extra recovery of the desirable constituent undiluted as much as possible by the more volatile undesirable constituent. To attain this objective it is necessary to carry out a more efficient fractionation at the primary point of contact between oil and gas which is in the absorber itself.

Fractionating Absorber. The fractionating absorber performs this duty, the schematic version of which is shown in Fig. 1. A gas cooler and partial condenser is an important adjunct of the absorber. It is equipped with a reboiler at the base of the stripping section and with one or more intercoolers at proper points in the absorption section. In the absorption section the less volatile fractions of the wet gas and of the vapors leaving the stripping section are absorbed and reabsorbed, respectively, according to wellknown laws in a descending stream of the lean oil; in the stripping section the undesirable more volatile fractions are being driven off through the application of heat to the reboiler and are returned to the absorption section. A recycle stream between the absorption and stripping sections is thus created and it is this stream which acts as the vehicle for the better separation between the key components. The action of the fractionating absorber may be better understood with the help of a few simple formulae which relate retention in the absorption section and rejection in the stripping section with overall recovery.

Let it be assumed that V mols of vapors and L mols of condensate enter the absorber above the top deck of the stripping section. L_o mols of a non-volatile lean oil enter at the top of the absorption section, Y mols of vapor leave the stripping section, X mols of downflow of absorbed fractions leave the absorption section. D mols and B mols, leave as off-gas and in the fat oil, respectively. Let α be the mol fraction of any component retained in the oil from the absorption section and let β be the mol fraction of any component rejected from the stripping section. Then, irrespective of the amount of oil circulated, one has as a material balance over the entire column

$$F = V + L = B + D$$

for the absorption section

$$\alpha(V + Y) = X \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and for the stripping section

$$\beta(L + X) = Y \quad . \quad . \quad . \quad . \quad . \quad (2)$$

also

$$(1 - \alpha)(V + Y) = D \quad . \quad . \quad (3)$$

$$(1 - \beta)(L + X) = B \quad . \quad . \quad (4)$$

by eliminating Y from (1) and (2)

$$X = \frac{V + \beta L}{1/\alpha - \beta} \quad . \quad . \quad . \quad . \quad (5)$$

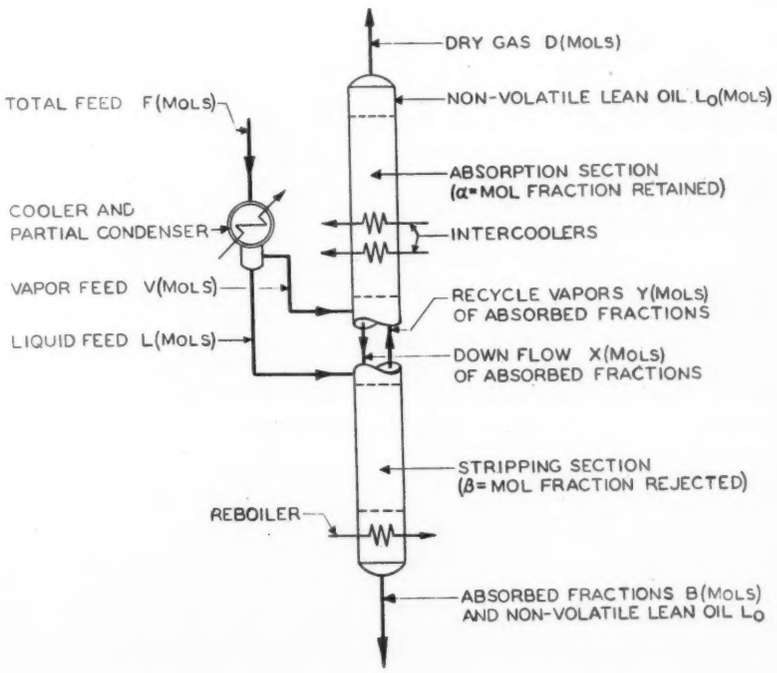
and by eliminating X, similarly

$$Y = \frac{\alpha V + L}{1/\beta - \alpha} \quad . \quad . \quad . \quad . \quad (6)$$

from (3), by substituting (6)

$$D \equiv D_1 + D_2 = \frac{1-\alpha}{1-\alpha\beta}(V + \beta L) \; . \quad (7)$$

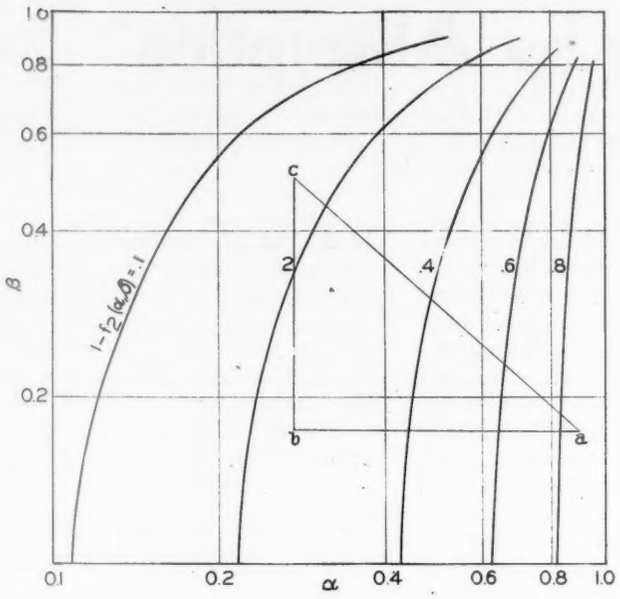
FIG. 1. Fractionating absorber.



*Presented before the Fall Meeting of California Natural Gasoline Association, 1948.

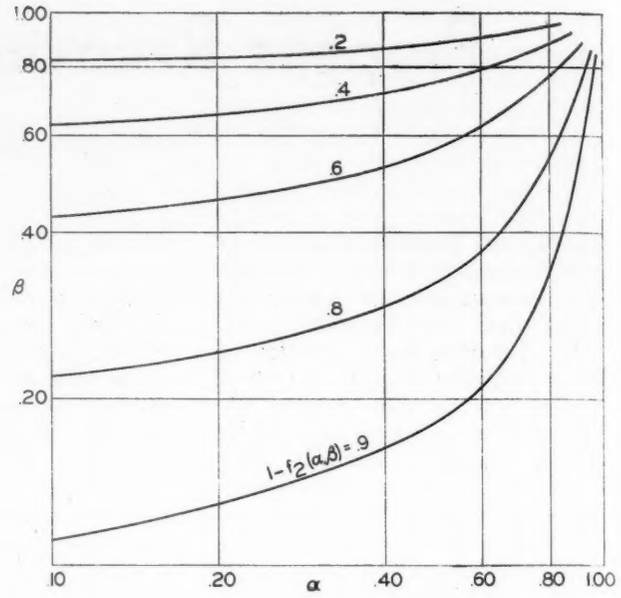
†The Lummus Company, New York.

FIG. 2.



Values of $1-f_1(\alpha,\beta) = 1-\frac{1-\alpha}{1-\alpha\beta}$

FIG. 3.



Values of $1-f_2(\alpha,\beta) = 1-\frac{1-\alpha}{1-\alpha\beta}\ \beta$

where

$$D_1 = \frac{1-\alpha}{1-\alpha\beta} V$$

or

$$D_1/V = \frac{1-\alpha}{1-\alpha\beta} \equiv f_1(\alpha_1\beta) \quad . \quad (8)$$

and

$$D_2 = \frac{1-\alpha}{1-\alpha\beta} \beta L$$

or

$$D_2/L = \frac{1-\alpha}{1-\alpha\beta} \beta \equiv f_2(\alpha_1\beta) \quad . \quad . \quad (9)$$

D_1 is obviously the fraction of any component in the vapor feed which is lost and D_2 is the fraction of any component in the liquid feed which is lost in the off-gas. The expressions $1-f_1$ (α, β) and $1-f_2$ (α, β) thus represent the fractions which are recovered. For $\beta=0$ which indicates no stripping D_1/V becomes $1-\alpha$ and $D_2/L=0$. For the same degree of retention α, the recovery decreases with an increase in the value of β, the degree of stripping, as the denominator $1-\alpha\beta$ becomes gradually smaller. But the amount by which the loss of D_1 increases, with an increase in β for constant α varies with α and β. This relationship is shown graphically in Fig. 2 where α and β are plotted to a logarithmic scale. For zero stripping the values of $1-f_1$ are of course equal to α and for a sufficient number of plates, such that linearity exists between α and the absorption factor A, they are also equal to A. The curves $f_1 = \text{const}$ show how α must be increased with an increase in β to obtain the same degree of recovery. Fig. 3 shows the degree of recovery $1-f_2$ of the condensate entering the stripper. The loss of f_2 is β times the corresponding loss of any constituent in the vapor feed. Without reabsorption, i.e. with $\alpha = 0$ the loss is β times the mols of a constituent in the liquid feed which is self-evident.

As an example, consider the separation of methane from ethylene in the following pyrolysis gas obtained from the cracking of propane:

TABLE 1. Composition of pyrolysis gas.

Component	Mol per cent
Hydrogen	10
Methane	25
Ethylene	25
Ethane	4
Propylene	17
Propane	16
Heavier	3
Total	100

Let it be assumed that the charge is all vapor and that the absorber is operated at 450 psig and 60 F and with an effective ethylene factor of .93. Without benefit of stripping there would be 22.5 mols of ethylene and 6.9 mols of methane recovered and the maximum ethylene purity obtainable which is set by the amount of methane dissolved in the lean oil would be approximately 77 mol per cent. Table 2 shows the results obtained with various degrees of stripping.

With moderate stripping, β (methane) = 0.5, the ethylene recovery would decrease to 88 per cent and the methane content of the ethylene product would decrease to approximately 15 mol per cent. With severe stripping, β (methane) = 0.9, the purity would be increased to 96 mol per cent while the recovery would drop further to 86 per cent.

These figures assume that the absorption factor is maintained by increasing the lean oil rate very nearly in proportion to the total volume of vapors entering. Actually both absorption and stripping rates may be varied within relatively wide limits to obtain satisfactory recovery and purity.

The same results may be read off directly from Fig. 2 where point "a" represents the α, β coordinates of ethylene and point "c" those of methane. The distance a-b is equal to the ratio of the α values and b-c equals the ratio of the β values. When $\alpha = A$ and $\beta = S$, which assuming 12 theoretical plates is true of values A and S of less than 0.8 the distances a-b and b-c are also equal to the ratios of the effective absorption and stripping factors or inversely proportional to the ratios of the equilibrium constants.

After establishing the α and β values for the key and all other components from the well-known graph of recovery vs. absorption factor and calculating the losses D by means of equation (6) one obtains the total vapor flow V + Y and, by difference, L + X, the total downflow to the stripping section. Knowing the effective absorb-

$$\frac{Y_{n+1}-Y_1}{Y_{n+1}-Y_o} = \frac{A_e^{n+1}-A_e}{A_e^{n+1}-1}$$

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As a result of this continual pioneering, *only* Powell makes such a complete line* that no matter what your flow control requirements may be, Powell has the valves to meet them. Moreover, Powell Engineers are always ready to help you solve any problems that might arise.

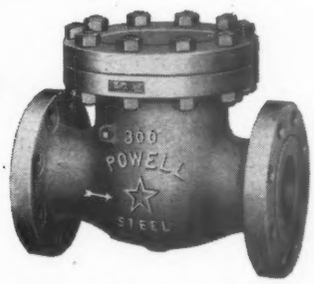


Fig. 3061—Class 300-pound Cast Steel Swing Check Valve. Flanged ends and bolted flanged cap.

Fig. 1793 — Large 125-pound Iron Body Bronze Mounted Gate Valve with outside screw rising stem, bolted flanged yoke, tapered solid wedge.

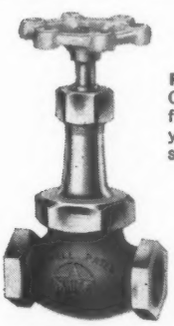


Fig. 102—200-pound Bronze Globe Valve with screwed ends, union bonnet and regrindable, renewable wear-resisting "Powellium" nickel-bronze seat and disc.

Fig. 9003—Class 900-pound Cast Steel Gate Valve with flanged ends, bolted flanged yoke, outside screw rising stem, tapered solid wedge.

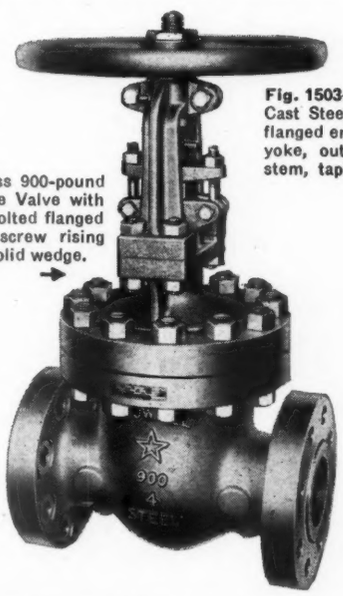
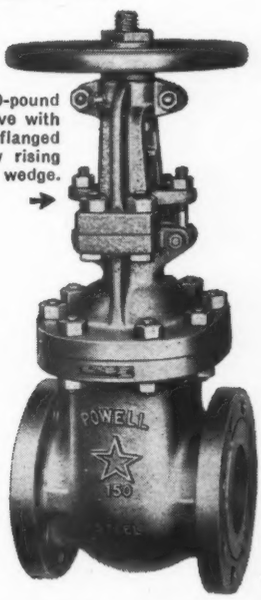


Fig. 1503—Class 150-pound Cast Steel Gate Valve with flanged ends, bolted flanged yoke, outside screw rising stem, tapered solid wedge.



*Powell Valves are made in Bronze, Iron, Steel and a wide selection of Corrosion-Resistant metals and alloys. Valves of every type—Globe, Angle, Gate, Check, Non-return and Flush Bottom Tank Valves—are included in the Complete Powell Line.

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TABLE 2. Effect of various stripping rates.

Comp	Charge	K_a	A	α	K_s	S	β	1—fl	B
β (Methane) = 0									
C_1	25	4.8	.275	.275	..	..	0	.275	6.9
C_2—	25	1.42	.93	.90	..	..	0	.90	22.5
β (Methane) = 0.5									
C_1	25	4.8	.275	.275	7.7	.50	.50	.16	.40
C_2—	25	1.42	.93	.90	2.67	.174	.174	.881	22.04
β (Methane) = 0.9									
C_1	25	4.8	.275	.275	7.7	.93	.90	.0366	.92
C_2—	25	1.42	.93	.90	2.67	.323	.323	.859	21.47

er and stripper temperatures from experience the lean oil rate may then be estimated from either the absorption or stripping factor by means of Edmister's[1] formulae as that value of L_O which yields the required α and β. Both values of L_O should be identical. If they do not coincide, which is to be expected after only one trial, it is very likely that the estimated temperatures are in error. The bottom absorber plate temperature and the top stripper plate temperature may be checked as dew and bubble points of Y and $X + L_O$, respectively, but these checks are very sensitive to small amounts of the heavy and light constituents included in Y and $X + L_O$, and the results must be interpreted with discretion. Nevertheless, it is not difficult for the designer of some experience to establish whether to increase or decrease the absorber and stripper temperature before he proceeds with a second caculation. Both temperatures have an effect upon the relative α and β, that is upon the direction of the line a-c above and small changes in α and β in the range where α or β is greater than 0.9 will cause noticeable changes in the lean oil rate.

This procedure holds rigorously only if the absorption oil contains no volatile constituents but may be used with sufficient accuracy in the absorption of natural gasoline if the lightest fractions of the lean oil and the heaviest fractions of the wet gas do not overlap. If the absorption oil has a volatility comparable to that of the recovered fractions of the wet gas the recycle vapor Y will contain a considerable volume of lean oil fractions and it will be impossible to establish the loss D and downflow X as explained above. In this case it is necessary to calculate the lean oil requirement in some preliminary way and to estimate the amount of stripping experienced by the lean oil on its descent in the absorption section. For the stripping section the lean oil may then be considered a part of L, the liquid feed from the partial condenser. The calculation of Y and of D follows, the latter now containing one additional term due to the presence of volatile lean oil. Equations may be derived for this case which lend themselves to a solution by successive approximations in the same manner as above. With liquid and vapor traffic and key temperatures known, a heat balance may may be drawn up which yields the amount of reboiling and intercooling required. The intercooling load is preferably distributed over several bundles in the absorption section. Internal cooling coils are more advantageous than the common intercoolers since with their use it is possible to realize a uniform temperature gradient rather than the saw tooth profile which is typical of external elements, but often it is not possible to accommodate the necessary surface within the available space. As a final check the L and V values at plates where heat is removed should be estimated and the absorption factor and lean oil rate checked by means of the explicit formulae of Horton and Franklin[2].

In plant operations it has been found that the performance of fractionating absorbers designed in accordance with this procedure exceeds the requirements anticipated in the design. In one instance where the design anticipated at 90 per cent recovery of the heavier key in the separation of methane from ethylene a recovery in excess of 96 per cent with better than design purity was obtained[3]. In another plant, the absorber design called for a 93.5 per cent recovery of the ethylene fraction from a combined stream of pyrolysis gas and thermal and catalytic depropanizer gases containing 19 mol per cent ethylene, 20.8 mol per cent methane and 7 mol per cent hydrogen and contaminants. The residual methane in the ethylene was to be not over 10.3 mol per cent referred to the recovered mixture of methane and ethylene. Actually the recovery exceeded 96 per cent consistently with a methane contamination of less than 5.0 mol per cent. Whether this gain in separation efficiency is due to the type of lean oil employed which contained substantial proportions of aromatics, particularly benzene or if it is the result of superimposed recirculation taking place between the plates where intercoolers are located has been the subject of speculation. A conclusively satisfactory explanation has not been found.

▸ **Plant Design with Fractionating Absorbers.** To demonstrate the value of fractionating absorbers in an installation of importance to the Natural Gasoline Industry it has been proposed to apply it to the recovery of propane from either a wet or a dry gas. This application has been worked out for a wet gas of the following composition:

TABLE 3. Composition of wet gas.

Component	Mol per cent
Methane	80.0
Ethane	6.0
Propane	8.0
Isobutane	1.0
N-butane	2.5
Pentanes plus	2.5
Total	100.0

To fix conditions further it has been assumed that the C_5 plus fraction would have the composition of the corresponding fraction in a typical Kettleman Hills natural gasoline, namely:

Component	Volume per cent
Pentanes	49
Hexanes	23
Heptanes plus	28
Total	100

The volatility of the pentanes fraction has been taken as that of a mixture composed of two-thirds isopentane and one-third N-pentane. Required is the recovery of 90 per cent of the propane, and of practically all of the butanes and heavier fractions. An absorption plant designed to meet these conditions is shown in Fig. 4. The main features of this design are: Use of two fractionating absorbers in series to obtain 90 per cent propane recovery, the propane to be of sufficient purity to pass the LPG vapor pressure specification (225 psig at 105 F) and use of the recovered natural gasoline as absorption oil. The wet gas in the present case is being delivered at 150 psig. To obtain economy in regard to initial investment and operating costs the absorber combination must be operated at a pressure upwards of 400 psig and at subatmospheric temperatures. As a fractionating absorber installation does not lend itself to the same degree of heat recovery as is common in a conventional absorption plant it is imperative to hold lean oil circulation

to a minimum to save utilities. An absorber pressure of 475 psig and lean oil temperature of 20 F have been chosen in the present case. As shown in Fig. 4 the wet gas is compressed in single stage compressors to 500 psig and cooled to 95 F. It is next dehydrated over fixed bed Bauxite driers to forestall the possibility of hydrate formation at temperatures below 60F, then cooled and partially condensed. It is convenient to cool the wet gas to the temperature of the entering lean oil, in this case 20 F. The first fractionating absorber—aptly called propane absorber—is operated with a lean oil rate of 6.3 gal per 1000 cu ft of wet gas and recovers 84 per cent or 220 mols per hour of propane with only 7.0 mols of ethane. The loss of lean oil to off-gas is on account of its extreme volatility very high, particularly in the pentane range. Calculated recoveries for the anticipated absorber conditions referred to wet gas quantities have been tabulated in Table 4.

It will be noted by reference to Table 4 that the primary purpose of the second absorber is the recovery of the volatile fraction of the lean oil. Only in a very minor degree does it contribute to an increase in propane recovery.

A detailed analysis shows that to obtain optimum results both absorbers should work in unison in the sense that the loan should be borne "equitably" by both. If, for instance, the first absorber recovers more than its share, the imposed stripping load will cause a disproportionate loss of butanes from the lean oil. Recovery of the lost butanes by the second absorber will cause the retention of excess ethane with the result that the LPG product will be off specifications. The opposite extreme would be a condition where the butane absorber has to recover more than its share of propane which would equally lead to ethane contamination of the LPG product unless absorption and stripping rates were adjusted to correct the condition. Table 5 shows the calculated streams compositions at important stations throughout the plant.

If the lean oil over the butane absorber equals in composition the C_7 and heavier fraction of the gasoline the calculated loss of lean oil will be 8.8 vol per cent of the yield of 16 RVP natural gasoline which is 113 gal per hour or 65 bbl per day, worth some $200 per day. To view this loss in proper perspective it must be borne in mind, however, that it is constituted of the least desirable fractions in regard to octane number and volatility of the recovered gasoline, and that it represents only 4.4 vol per cent of the LPG fraction and only 2.0 vol per cent of the total yield of liquid products. The loss may be decreased at the expense of an increase in oil circulation by using instead of the heptanes plus fraction only the last 15 vol per cent or even 10 vol per cent of the natural gasoline, as lean oil in the butane absorber. It is necessary to replenish the inventory of lean oil circulating over the butane absorber continuously. This is done by passing an adequate amount of the gasoline over the still which removes the recovered fractions from the butane absorber fat oil. The still overhead which has the composition shown in Table 5 and the propane absorber bottoms are partially debutanized in the debutanizer to leave a 16 RVP gasoline product. The overhead from the debutanizer is then passed to the depropanizer which produces an LPG propane as overhead and excess butanes as bottoms.

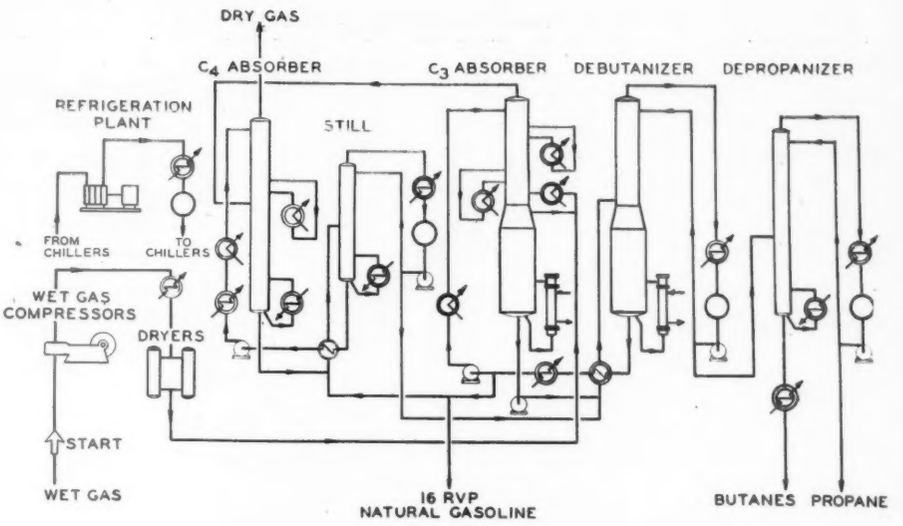

FIG. 4. Absorption plant for high propane recovery.

Refrigeration is furnished by a conventional compression type refrigeration unit, using LPG-propane as refrigerant, at two temperature levels 40 F and 10 F, to obtain a minimum cost installation. At the lower level, 7.6 million BTU per hr are dissipated, the greater part by the absorber intercoolers. At the 40 F level 3.6 million BTU per hr are removed. Approximately 1540 bhp of compressor capacity are required for this load. Wet gas compression accounts for 2200 bhp, so that the total compressor capacity is approximately 3740 bhp, all of it gas engine driven.

TABLE 4. Calculated recoveries, per cent.

Component	Propane absorber	Butane absorber	Total
Methane	0.0	0.0	0.0
Ethane	3.53	1.77	5.30
Propane	83.73	6.27	90.0
Isobutane	69.1	29.4	98.5
N-butane	64.4	34.8	99.2
Pentanes	33.8	66.2	100.0
Hexanes	85.5	13.3	98.8
Heptanes	95.8	—25.3	70.5

A lean oil conditioning still is not required. To prevent a build-up of heavy ends over the butane absorber and still, it is sufficient to circulate a small stream of still bottoms over the debutanizer tower.

Utility requirements have been calculated at 84 million BTU per hr equivalent to 80,000 scf of dry gas, 155 gpm of makeup water and 350 kw of electric power. The plant is self-contained in regard to steam, so that steam could be included at its equivalent fuel gas value. The cost of utilities is shown in Table 6 based on 10 cents per million BTU's, 6.7 cents per 1000 gal of makeup water and 1.0 cents per kwh. These figures include the requirements for steam generation and of the cooling water plant.

▶ **Cost Comparison.** As shown in Table 5 the plant, when recovering 90 per cent of the available propane from 30 million cu ft of wet gas, will produce 62,000 gal of specification LPG-propane, 29,000 gal of butanes and 31,000 gal of natural gasoline, a total of 122,000 gal of liquid products daily. The market value of these products at current prices of 6.0 cents per gal for LPG, 6.8 cents per gal for butane and 9.4 cents per gal for the 16-55 grade of natural gasoline is $8590.

Direct operating expenses consist of labor and supervision—5 men per shift—$228, utilities $319 and the general works expense item of $312, which includes repairs, laboratory, shop and warehouse, and that part of the administrative expense and administrative overhead directly charge-

TABLE 5. Stream compositions—Mols per hr.

Stream	(1)	(2)	(3)	(4)	(5)
Component	Wet gas	Vapor to absorber	Liquid to absorber	C^3 abs off-gas	Lean oil to C^3 abs
Methane	2640	2569.5	70.5	2640	
Ethane	198	173.5	24.2	191	
Propane	264	182.9	81.1	42.9	
Isobutane	33	15.8	17.2	10.2	22
N-butane	82.5	32.1	50.4	29.3	88
Pentanes	46.2	8.1	38.1	30.6	254
Hexanes	17.3	.7	16.6	2.5	104
Heptanes	19.0	.2	18.8	0.8	82
Total	3300.0	2983.1	316.9	2947.3	550
Lb per hr	73,209	57,815	15,394	54,647	41,812
MW	22.18	19.38	48.57	18.54	76.02
Gal per hr	..	..	..	..	7884.2
Lb per hr	..	..	..	..	5.30
MCFD	30,017	27,134	2,883	26,809	..

Stream	(6)	(7)	(8)	(9)	(10)
Component	Fat oil from C^3 abs	C_4 abs off-gas	Lean oil to C_4 abs	Fat oil from C_4 abs	Stripper makeup
Methane	..	2640	..	..	..
Ethane	7.0	187.5	..	3.5	..
Propane	221.1	26.4	..	16.5	..
Isobutane	44.8	0.5	..	9.7	4.0
N-butane	141.2	0.6	..	28.7	16.0
Pentanes	269.6	..	..	30.6	46.2
Hexanes	118.8	0.2	3.3	5.6	18.9
Heptanes	100.2	5.6	326.7	321.9	14.9
Total	902.7	2860.8	330.0	416.5	100.0
Lb per hr	60,374	49,668	32,954	37,933	7602.0
MW	66.88	17.36	99.86	91.07	76.02
Gal per hr	11,917.5	111.5*	5711.8	6754.3	1433.4
Lb per gal	5.07	..	5.77	5.62	5.30
MCFD	..	26,022	..	..	..

*C_4 and heavier only.

Stream	(11)	(12)	(13)	(14)	(15)
Component	Stripper oil OH	Debut feed	16 RVP nat. gasoline	LPG	Butanes
Methane	..	..	..	..	..
Ethane	3.5	10.5	..	10.5	..
Propane	16.5	287.6	..	237.1	.5
Isobutane	13.7	58.5	3.6	1.1	27.8
N-butane	44.7	185.9	14.4	1.5	66.0
Pentanes	76.8	346.4	41.6	..	4.6
Hexanes	21.2	140.0	17.0	..	.1
Heptanes	10.1	110.3	13.4	..	..
Total	186.5	1089.2	90.0	250.2	99.0
Lb per hr	12,581.0	72,955	6841.0	10,898.0	5802.0
MW	67.46	66.98	76.01	43.56	58.60
Gal per hr	2476.0	14,393.4	1290.0	2585.1	1200.6
Lb per gal	5.08	5.07	5.30	4.22	4.83
MCFD	..	..	..	..	..

able against production. The aggregate of these costs is $857 per day; the direct cost of production is thus .705 cents per gal of total liquid products recovered. This figure is lower than is obtained in most conventional plants handling an equal gas volume and recovering gasoline and butanes only. By comparison it is interesting to note that the fuel value of the products recovered at 1 cent per therm is .911 cents per gal.

There remains the question of initial cost. Contributing to an increase in cost over the conventional absorption plant will be the additional gas compression and the refrigeration plant. Also the drier installation, which, while necessary for the operation of the plant, benefits the purchaser of the dry gas as well. On this account the cost of the drier installation may under certain circumstances be recoverable through increased revenue from the sale of the dry gas. More than balancing these increases, however, is the savings in lean oil circulation, which amounts to only 10.9 gal per 1000 cu ft of wet gas. The completely erected cost has thus been estimated as of the order of $1,900,000. Included in this figure are the estimated cost of the plant proper with 3 days' pressure storage for butanes and 3 days' atmospheric storage for natural gasoline, also steam generation, cooling tower and cooling water pumping plant. Not included are the cost of propane storage, loading facilities, spurs, roads and lines outside the process area or between storage and process area.

TABLE 6. Utility requirements and costs.

		Dollars per day
Fuel gas	84.22 million Btu per hr	200
Makeup water	155 gpm	15
Electric power	350 kwh per hr	84
Desiccant and miscellaneous		20
Total		319

Modifications of Existing Plants for Increased Propane Recovery. If it is conceded that these figures of operating costs and investment are attractive, it may well be asked what modifications to existing plants may be made to increase propane recovery. In the light of what has been said above no all inclusive answer to this question can be given. As mentioned, several measures may be taken in an existing plant to increase the recovery of butanes, propane, or even of ethane and optimum results may be achieved through a combination of these measures.

If it were required to expand a plant extracting 95 per cent of the normal butane from the wet gas of Table 3 such that 90 per cent of the propane would be recovered the most likely solution would be to replace the existing absorber with a fractionating absorber installation operating at a pressure and temperature such that the lean oil circulation would not exceed that of the existing plant. While this lead oil circulation in straight absorption would result in a normal butane factor of approximately 1.1 (12 plates) the same circulation would have to produce a propane factor of 0.97 for a considerably increased volume (due to internal recycle) of vapors. It is not difficult to find combinations of pressure and temperature which will satisfy this condition; the problem is to determine which of the possible combinations will yield the plant of lowest cost. Increasing the absorber pressure from an initial value of 150 psig, the first additional compression ratio is equivalent to a lowering of the effective absorber temperature by 60 F, the next one to only 37 F and the third to only 22 F. Refrigerating the lean oil will be found relatively more expensive below pressures of 450 psig than will wet gas compression.

Acknowledgment. The author is indebted to The Lummus Company for permission to publish this paper and to Dr. E. R. Smoley for assistance in its general aspects. He is grateful to Messrs. M. J. P. Bogart, W. Tucker and J. A. DiPace, all of The Lummus Company, who have perfected the design method and who have performed the necessary calculations in the case of the above absorption plant.

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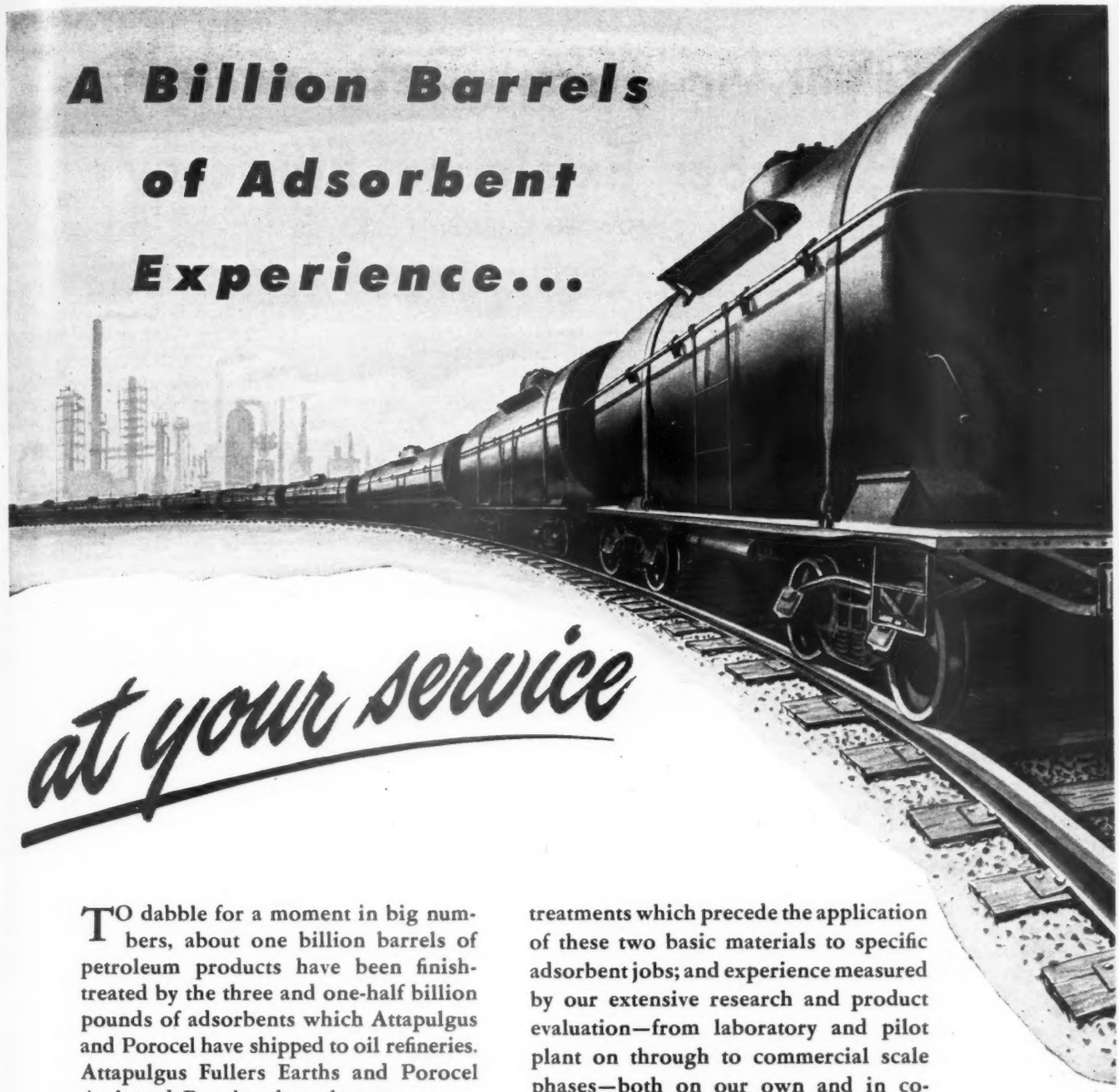

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Straight-Line Chart Determination of Absorber Extraction Efficiency*

By EDWARD G. RAGATZ

The recently proposed Straight-line Chart method of absorber analysis has been broadened and refined with the resultant development of a highly significant overall performance factor. This factor has been given the designation of extraction efficiency, and expresses the ratio (in terms of per cent) of the theoretical minimum to actual lean oil rate required to effect a 95 per cent butane recovery at any particular absorber effectiveness under any given base conditions of absorber operation. Application of this factor to a wide range of commercial units indicates the possibility of markedly improving the effectiveness of present day high pressure absorbers.

A TECHNIQUE based on an experimentally developed Straight-line Absorption Chart was recently proposed† for meeting the following requirements of a universal method of evaluating absorber operating effectiveness:

(1). Use only "terminal" operating data readily obtainable from any normal commercial absorber installation.

(2). Directly evaluate the absorber's effectiveness under actual conditions of operation without reference to divergencies from original conditions of design.

(3). Avoid the use of estimated or calculated "internal" factors or conditions, thus eliminating all need for employment of personal judgment in analyzing the column test data.

(4). Designate the column's effectiveness for recovery of both isobutane and n-butane by the same number, thus avoiding the "dual efficiency" complications encountered with the classical Kremser-Brown analysis at higher pressures.

(5). Provide an automatic check on the validity of both the test data proper, and the laboratory analyses of the test samples.

During the last year this Straight-line Chart method of analysis has been applied to the study of a large number of special tests on absorbers ranging in pressure from 50 to 1800 psig. As a result, the original chart layout has been refined in considerable detail, and an "Extraction Efficiency" factor derived therefrom whereby the overall column effectiveness under any given operating condition may be defined by a single consistent evaluating number.

Fig. 1 is representative of our latest conception of the Straight-line Chart. As indicated, it now consists of a main "Per Cent Recovery vs. A_ε" grid and a complementary "Operating Pressure vs. A_ε' sub-grid—with a "Per Cent Recovery" reference line drawn across the sub-grid to facilitate plotting recovery points that fall on the sub-grid portion of the chart (i.e. recoveries below 80 per cent). An appropriate form is also provided for tabulation of pertinent column test data.

The formula for calculating the A_ε of the chart has also been further simplified—now being expressed as:

$$A_\varepsilon = \left\{ \left[\frac{R_B}{R_T} \times A_T \times (1 + A_T) \right] + 0.25 \right\}^{\frac{1}{2}} - 0.50$$

Where:

$$R_B = \left(\frac{L}{V}\right)_B = \frac{\text{Mols rich oil}}{\text{Mols rich gas}}$$

$$R_T = \left(\frac{L}{V}\right)_T = \frac{\text{Mols lean oil}}{\text{Mols lean gas}}$$

$$A_T = R_T \times \frac{1}{K}$$

K = Equilibrium coefficient of component in question at column pressure and rich oil temperature.

This latest form of the Straight-line Chart presents the following analytical characteristics when applied to various conditions of absorber operation and control.

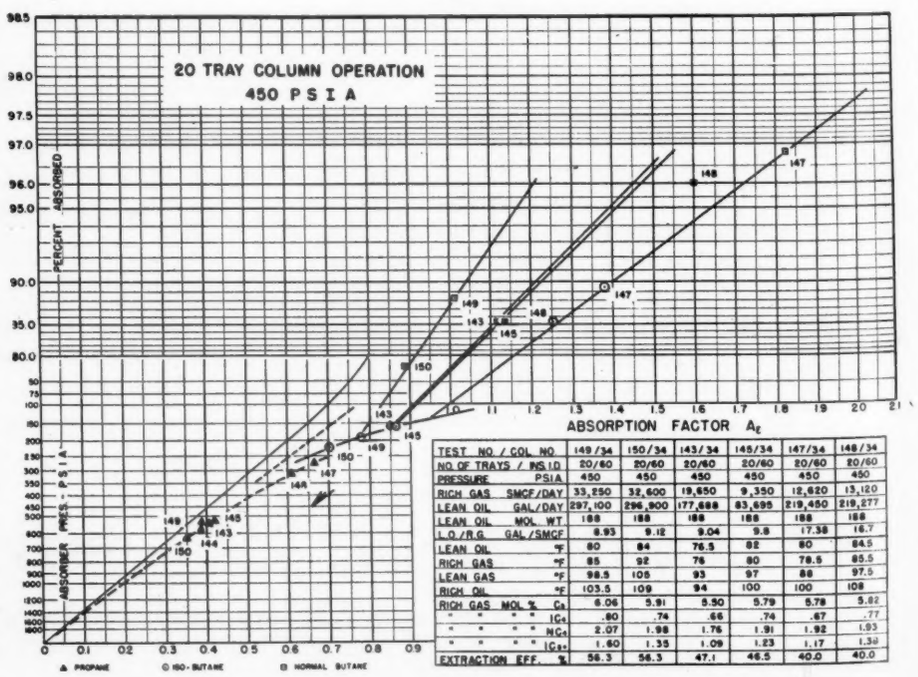
A. In a given column handling a given composition of rich gas at a given pressure under simple (i.e. non-intercooled) conditions of operation with properly stripped lean oil:

(1). If the volumes of rich gas and lean oil are held constant, and the temperatures of the lean oil and rich gas are changed in approximately the same amount over a fairly small range, or the molecular weight of the lean oil is changed, the resultant recoveries of isobutane and n-butane will change, and all such recoveries above a fairly fixed minimum value (ranging from 75-80 per cent at 60 psia down to some 35-40 per cent at 2000 psia) will be found to lie on a single straight line when plotted against their appropriate A_εs on the Straight-line Chart.

These lines have been designated "Operating Lines" in our analytical procedure, and are used to evaluate the column's operating efficiency.

(2). If the rich gas or lean oil vol-

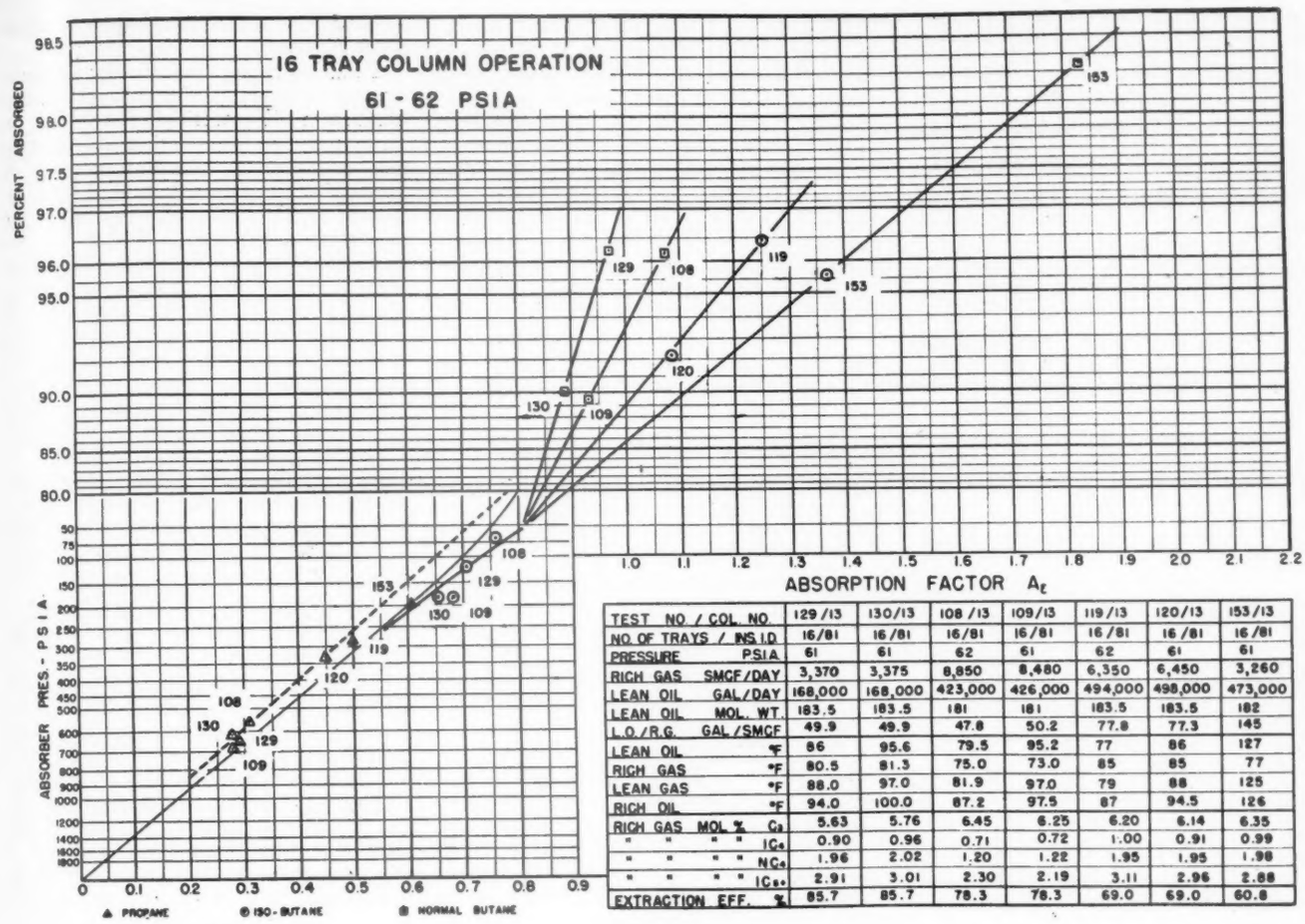
FIG. 1.


20 TRAY COLUMN OPERATION
450 P S I A
PERCENT ABSORBED
ABSORBER PRES. - PSIA
ABSORPTION FACTOR A_ε
▲ PROPANE ○ ISO-BUTANE □ NORMAL BUTANE

TEST NO. / COL. NO	149/34	150/34	143/34	145/34	147/34	148/34
NO. OF TRAYS / INS I.D	20/60	20/60	20/60	20/60	20/60	20/60
PRESSURE PSIA	450	450	450	450	450	450
RICH GAS SMCF/DAY	33,250	32,600	19,650	9,350	12,620	13,120
LEAN OIL GAL/DAY	297,100	296,900	177,688	83,695	219,450	219,277
LEAN OIL MOL. WT	188	188	188	188	188	188
L.O./R.G. GAL/SMCF	8.93	9.12	9.04	9.8	17.38	16.7
LEAN OIL °F	80	84	76.5	82	80	84.5
RICH GAS °F	85	92	76	80	78.5	85.5
LEAN GAS °F	98.5	105	93	97	88	97.5
RICH OIL °F	103.5	109	94	100	100	108
RICH GAS MOL % C_3	6.06	5.91	5.50	5.79	5.78	5.82
" " " iC_4	.80	.74	.66	.74	.67	.77
" " " nC_4	2.07	1.98	1.76	1.91	1.92	1.93
" " " iC_5	1.60	1.35	1.09	1.23	1.17	1.34
EXTRACTION EFF. %	56.3	56.3	47.1	46.5	40.0	40.0

*Presented before joint meeting of California Natural Gasoline Association and Southern California Section of American Institute of Chemical Engineers, December 10, 1947.

†"Evaluation of Absorber Operating Efficiency" by Ragatz and Richardson. Paper presented at 1946 Fall Meeting of the California Natural Gasoline Association.



TEST NO / COL. NO.	129/13	130/13	108/13	109/13	119/13	120/13	153/13
NO OF TRAYS / INS.I.D	16/81	16/81	16/81	16/81	16/81	16/81	16/81
PRESSURE PSIA	61	61	62	61	62	61	61
RICH GAS SMCF/DAY	3,370	3,375	8,850	8,480	6,350	6,450	3,260
LEAN OIL GAL/DAY	168,000	168,000	423,000	426,000	494,000	498,000	473,000
LEAN OIL MOL. WT.	183.5	183.5	181	181	183.5	183.5	182
L.O./R.G. GAL/SMCF	49.9	49.9	47.8	50.2	77.8	77.3	145
LEAN OIL °F	86	95.6	79.5	95.2	77	86	127
RICH GAS °F	80.5	81.3	75.0	73.0	85	85	77
LEAN GAS °F	88.0	97.0	81.9	97.0	79	88	125
RICH OIL °F	94.0	100.0	87.2	97.5	87	94.5	126
RICH GAS MOL % C_3	5.63	5.76	6.45	6.25	6.20	6.14	6.35
" " " " IC_4	0.90	0.96	0.71	0.72	1.00	0.91	0.99
" " " " NC_4	1.96	2.02	1.20	1.22	1.95	1.95	1.98
" " " " IC_{5+}	2.91	3.01	2.30	2.19	3.11	2.96	2.88
EXTRACTION EFF. %	85.7	85.7	78.3	78.3	69.0	69.0	60.8

FIG. 2.

FIG. 3.

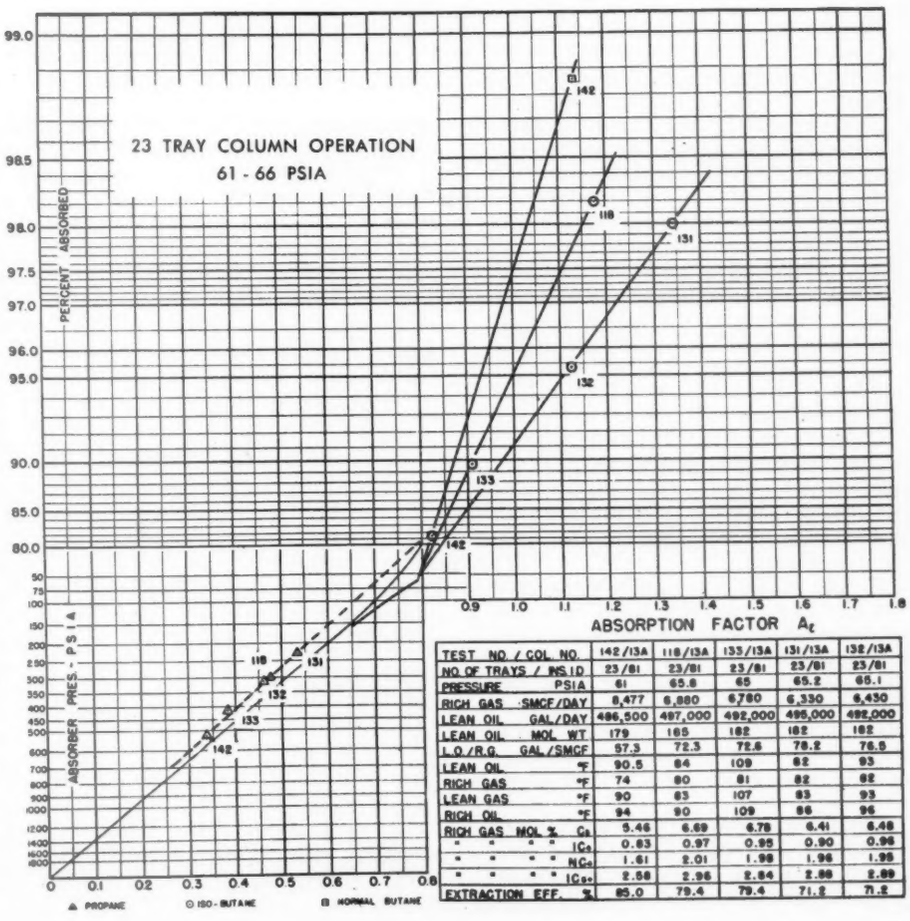
umes are then changed, and the temperature procedure of (1) above repeated, a series of operating lines of varying slopes will be defined, all intersecting at a common focal point on the operating pressure grid as long as the base conditions of "A" above remain fixed.

(3). If the number of trays, or the detailed tray design, is changed and the above procedure repeated, different groups of operating lines will be formed. All such groups, however, will have approximately the same common focal point as long as the base conditions of "A" above remain fixed.

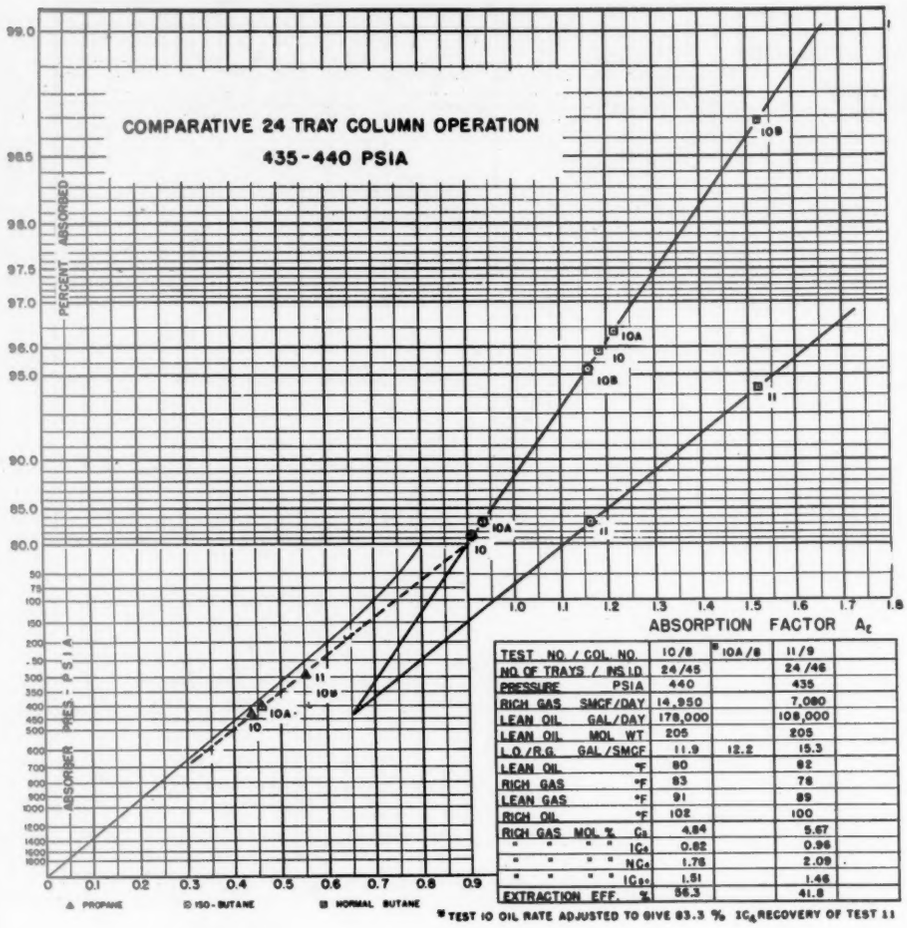
B. If the column pressure is changed, the focal point will then shift both vertically and laterally, with this shift being downward and normally to the left with increasing pressure.

C. If the quality or temperature of the rich gas, or the temperature of the lean oil, is changed appreciably while holding the operating pressure constant, the focal point will shift laterally along an appropriate horizontal "Operating Pressure" line. Under conditions of extreme temperature change, the slope of the operating line may also shift slightly, with this latter shift being due to a substantial change in the fractionation effect associated with internal recycling of key component fractions.

D. If intercooling is employed, the focal point will again shift laterally along an appropriate "Operating Pressure" line, with the degree and direction



TEST NO / COL. NO.	142/13A	118/13A	133/13A	131/13A	132/13A
NO OF TRAYS / INS.I.D	23/81	23/81	23/81	23/81	23/81
PRESSURE PSIA	61	65.8	65	65.2	65.1
RICH GAS SMCF/DAY	8,477	6,880	6,780	6,330	6,430
LEAN OIL GAL/DAY	486,500	487,000	492,000	495,000	492,000
LEAN OIL MOL WT	179	185	182	182	182
L.O./R.G. GAL/SMCF	57.3	72.3	72.6	78.2	76.6
LEAN OIL °F	90.5	84	109	82	93
RICH GAS °F	74	80	81	82	82
LEAN GAS °F	90	83	107	83	93
RICH OIL °F	94	90	109	86	96
RICH GAS MOL % C_3	5.46	6.69	6.78	6.41	6.48
" " " " IC_4	0.83	0.97	0.95	0.90	0.96
" " " " NC_4	1.61	2.01	1.98	1.96	1.96
" " " " IC_{5+}	2.86	2.96	2.84	2.86	2.89
EXTRACTION EFF. %	85.0	79.4	79.4	71.2	71.2


COMPARATIVE 24 TRAY COLUMN OPERATION
435-440 PSIA
PERCENT ABSORBED
ABSORBER PRES - P.S.I.A.
ABSORPTION FACTOR A_ε
△ PROPANE ○ ISO-BUTANE □ NORMAL BUTANE
* TEST 10 OIL RATE ADJUSTED TO GIVE 83.3 % IC_4 RECOVERY OF TEST 11

TEST NO. / COL. NO.	10/8	*10A/8	11/9
NO OF TRAYS / INS.ID	24/45		24/46
PRESSURE PSIA	440		435
RICH GAS SMCF/DAY	14,950		7,080
LEAN OIL GAL/DAY	178,000		108,000
LEAN OIL MOL WT	205		205
L.O./R.G. GAL/SMCF	11.9	12.2	15.3
LEAN OIL °F	80		82
RICH GAS °F	83		78
LEAN GAS °F	91		89
RICH OIL °F	102		100
RICH GAS MOL % C_3	4.84		5.67
" " " " IC_4	0.82		0.96
" " " " NC_4	1.76		2.09
" " " " IC_{5+}	1.81		1.46
EXTRACTION EFF. %	56.3		41.8

FIG. 4.

loading are clearly indicated in these three figures.

Each operating line on each of these figures is analagous to a single Kremser-Brown "Theoretical Tray" line in that it shows the relationship existing between a given per cent recovery of iso-butane or n-butane, and the A_ε required to effect that recovery under the operating conditions reflected by the particular line in question. And since there are a series of lines of varying slope (i.e. different A_ε values for a given per cent butane recovery) for each of the columns, it is evident that the effectiveness of the individual columns varies with the varying operating conditions associated with the individual operating lines.

Now relative column effectiveness may be evidenced by different oil-gas ratios for the same key component recovery, or by different recoveries for the same oil-gas ratio, other operating factors being equal. And since $A_\varepsilon = f\left(\frac{L}{V} \times \frac{1}{K}\right)$, if the factors controlling "K" are held constant, then the oil-gas ratios required to effect a given butane recovery should be directly proportional to A_ε.

Under these circumstances the steepest lines of Figs. 1 and 2 indicate an oil-gas ratio requirement of only 71 per cent that of the flattest line to effect a 95 per cent recovery of butane, while the steepest line of Fig. 3 indicates an 85 per cent requirement for a similar comparative recovery.

Oil-gas ratio differences of this order are of major importance, and Fig. 4 presents data on a 20-tray column operating at 450 psia, and Figs. 2 and 3 data on 16-tray and 23-tray columns of identical tray designs operating at 60-65 psia. The marked changes in operating line slope normally associated with substantial changes in absorber tray loading are clearly indicated in these three figures.

of this shifting being dependent on the amount and location of intercooling employed.

The functional background for these analytical characteristics of the Straight-line Chart may be summarized as follows:

A. The *slope* of the *operating line* is a function of:

(1). The number of trays employed.

(2). The adaptability of a given tray design to the particular volumetric vapor-liquid load imposed upon it.

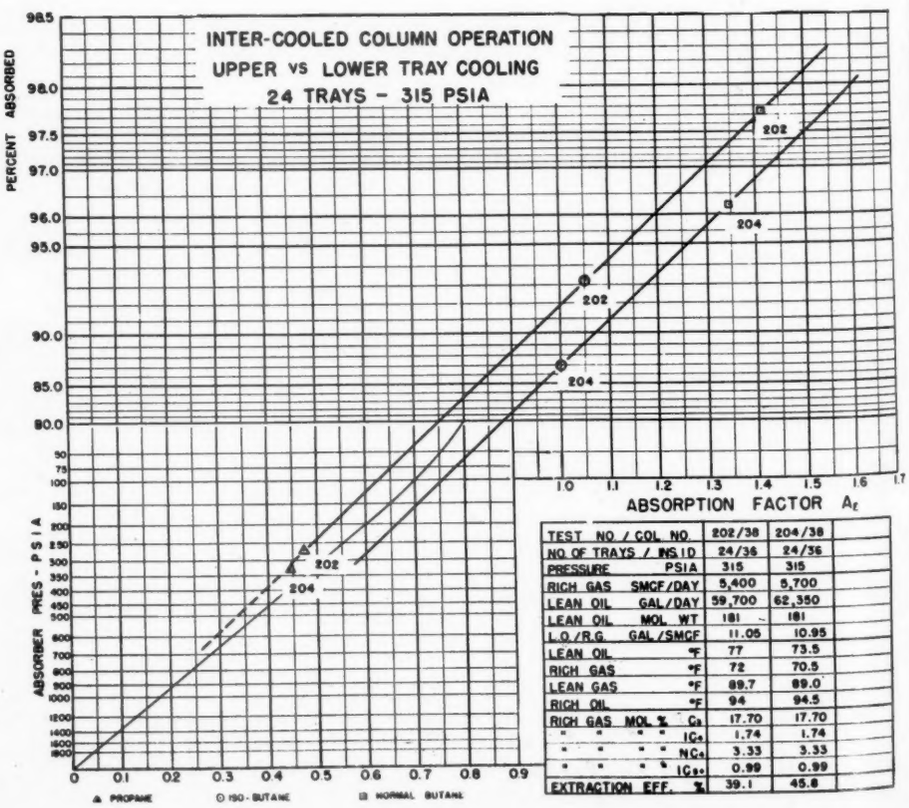
(3). The degree of internal recycling developed by differences in lean oil and rich gas temperatures.

B. The *vertical location* of the operating line *focal point* is a function of the relative absorptive responsiveness of butanes to changes in lean oil rate and, as such, is primarily influenced by operating pressure.

C. The *lateral location* of the operating line *focal point* is a function of the relationship existing between the true integrated mean absorption factor and the empirical A_ε of the analysis. As such, it is sensitive to operating pressure, rich gas quality, temperature differences between lean oil and rich gas, and degree and location of column intercooling.

Typical examples of operating lines radiating from common focal points are shown in Figs. 1, 2, 3 in which Fig. 1 presents data on a 20-tray column op-

FIG. 5.


INTER-COOLED COLUMN OPERATION
UPPER VS LOWER TRAY COOLING
24 TRAYS - 315 PSIA
PERCENT ABSORBED
ABSORBER PRES - P.S.I.A.
ABSORPTION FACTOR A_ε
△ PROPANE ○ ISO-BUTANE □ NORMAL BUTANE

TEST NO / COL NO.	202/38	204/38
NO OF TRAYS / INS ID	24/36	24/36
PRESSURE PSIA	315	315
RICH GAS SMCF/DAY	5,400	5,700
LEAN OIL GAL/DAY	59,700	62,350
LEAN OIL MOL WT	181	181
L.O./R.G. GAL/SMCF	11.05	10.95
LEAN OIL °F	77	73.5
RICH GAS °F	72	70.5
LEAN GAS °F	89.7	89.0
RICH OIL °F	94	94.5
RICH GAS MOL % C_3	17.70	17.70
" " " " IC_4	1.74	1.74
" " " " NC_4	3.33	3.33
" " " " IC_{5+}	0.99	0.99
EXTRACTION EFF. %	39.1	45.8

sents direct evidence that their magnitude is truly reflected in the slope of the Straight-line Chart operating lines.

Fig. 4 presents test data on two 24-tray, 435-440 psia columns of radically different tray design operating with the same molecular weight oil on similar quality rich gas at similar lean oil and rich gas temperatures for the production of approximately the same isobutane recoveries (81.3 per cent vs. 83.4 per cent). Under such circumstances, only a small adjustment need be made in the oil-gas ratio of one column to exactly duplicate the iso-butane recovery of the second, and the amount of such adjustment can be readily calculated.

Such a calculation was made for Test 10 of Fig. 4 under the designation of Test 10A. With this adjustment the chart data shows that column 8, operating under substantially the same temperature conditions as column 9, would recover the same percentages of isobutane, and 2 per cent more n-butane, than column 9 while employing a lean oil circulation rate only 80 per cent (i.e. 12.2 vs 15.3 gal/std M cu ft) of that of column 9—and in keeping with the previous discussion on operating line slope, the isobutane A_ε of Test 10A is correspondingly found to be 80 per cent that of the isobutane A_ε of Test 11.

While oil circulation rates for a given butane recovery may be thus reduced by the use of more effective columns, associated propane recoveries will be reduced in proportion to the oil-gas ratio reduction. This does not mean, however, that the more efficient column has no merit in the case of desired higher propane recoveries. Rather, it means that (for example) if the higher oil rate of Test 11 were retained for maintenance of a higher propane recovery, then the use of such a higher oil rate in an absorber exhibiting the effectiveness of column 8 would increase the isobutane recovery from 83.4 per cent to some 95.2 per cent, and the n-butane recovery from 94.3 per cent to some 98.7 per cent, as indicated by points 10B of Fig. 4.

A pair of operating lines from a special intercooled column test is presented on Fig. 5. In this particular test the lean oil and rich gas rates were held substantially constant, and cooling applied first near the top and then near the bottom of the column for the maintenance of a substantially constant rich oil outlet temperature. Operating Line 202 of Fig. 5 represents the upper tray cooling run, and line 204 the lower tray cooling run, of this test.

The superiority of upper over lower tray cooling for this particular operation is self-evident, while from the Straight-line Chart angle it is to be noted that this superiority is evidenced by a parallel leftward displacement of the operating line focal point in the case of the more efficient run. Such horizontal shifting of the operating line focal point is characteristic of changes in location or degree of column intercooling, or wide changes in rich gas-lean oil temperature differences.

From evidence presented by a large amount of test data similar to those of Figs. 1-4, it can be postulated that increases of operating line slope approach infinity as a limit, and that at such limit, the base focal point A_ε is directly analagous to the classical conception of a "Minimum Reflux Ratio" for an infinite number of trays. This "Minimum A_ε" concept, in turn, provides a rational basis for reduction of operating line values to a 'Single Number" evaluating factors, which factor we have designated as the:

Overall Extraction Efficiency "EE" and defined as:

$$\text{"EE"} = \frac{A_\varepsilon \text{ of the operating line focal point}}{A_\varepsilon \text{ of the operating line at 95 per cent recovery}} \times 100$$

The choice of a 95 per cent recovery base for this efficiency factor was purely arbitrary; however, it was a logical choice in that it represents a fair mean of the higher efficiency isobutane and n-butane recovery operations currently employed in the industry, and falls at a convenient reference zone on the Straight-line Chart.

It should be emphasized that this overall "Extraction Efficiency" factor is distinctly different from the classical individual "Tray Efficiency" factor in that:

(1). It is a measure of *overall column* effectiveness rather than *individual tray* effectiveness.

(2). Although accurately defining the slope of the column operating line for any butane recovery, as a direct evaluative number it applies only to a 95 per cent recovery.

(3). As such, it expresses the approximate ratio (in terms of per cent) of the theoretical minimum to the actual amount of lean oil required to effect a 95 per cent butane recovery under the particular base operating conditions in question (i.e. column pressure, lean oil temperature, and rich gas temperature and quality).

Obviously, where the operation of the column as a whole is the primary interest, such an overall evaluating factor carries much more significance than the classical individual tray efficiency factor.

Given such an evaluating factor and the previously outlined focal point characteristics of the Straight-line Chart, it is seen that the operating effectiveness of any column under any condition of operation can accurately be defined by two numbers, namely:

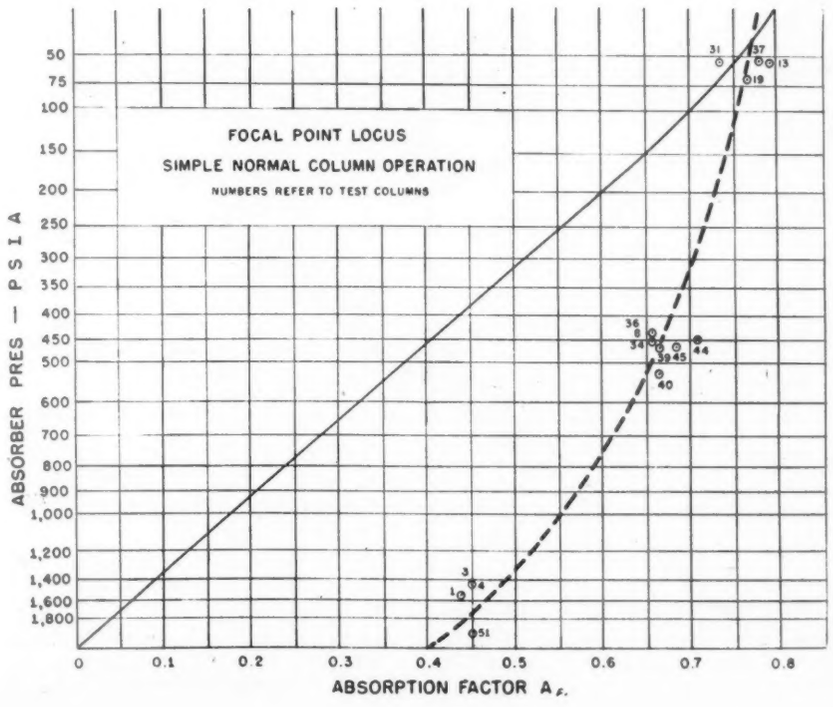
(1) The Extraction Efficiency "EE",

(2) The A_ε of the operating line focal point.

In the case of simple normal operating columns (i.e. non-intercooled columns operating on rich gases of normal composition at normally encountered rich gas/lean oil temperatures) the basic conditions of the column operation are primarily controlled by the operating pressure, and all focal points cling closely to a single mean "Operating Pressure—Focal Point A_ε" line. Under these conditions, designation of a focal point A_ε can often be dispensed with, and a first order measure of column effectiveness defined by "Extraction Efficiency" alone.

Fig. 6 presents an enlargement of the pressure sub-grid of the Straight-line Chart on which we have plotted a series of well-defined focal points for a number of normal operating columns rang-

FIG. 6.



ing in pressure from 50 to 1800 lb ga. Study of this figure shows that only a secondary order of difference in butane yield is indicated as between using an actual test defined focal point, and a corresponding mean focal point from the heavy dashed "Locus Line" of the figure.

While procurement of additional test data may result in a future shifting of this normal locus line in the high pressure region, it is thought to be already quite well-defined for pressures up to 600 psia.

Identification and evaluation of propane recoveries is also a function of the Straight-line Chart. As would be expected, the propane recovery lines are distinct from the butane recovery lines, and are independent of the overall operating effectiveness of most simple commercial columns up to recoveries of the order of 75-80 per cent. However, these lines do shift significantly with operating pressure.

In Fig. 7 we present an enlarged section of the Straight-line Chart pressure grid on which we have indicated:

(1). Typical propane recovery lines for "normal" columns at four different operating pressures.

(2). A "50 psia Intercept" base guide line whereby one can draw a mean "normal" propane recovery line for any desired operating pressure.

To use this chart, find the A_ε value of the intercept of the subject operating pressure line with the propane base guide line, and draw a straight line from 0-0 of the Chart to this A_ε value at the 50 psia line. Normal propane recoveries for the more efficient commercial columns will coincide with this straight line up to values of the order of 60-65 per cent recovery, and thence curve slightly upward to 75-80 per cent in keeping with the pattern set by the several recovery lines of Fig. 7. To date we have no data on recoveries of more than 85 per cent.

In using this mean "normal" propane recovery chart, it should be noted that propane recoveries will increase over the mean line value with extra low rich gas and/or lean oil temperatures, and decrease with extra high temperatures. Unfortunately, we have not accumulated sufficient data to date to permit of correlating such deviations with the actual temperature differences. It should also be noted that propane recoveries will fall below their mean line values in cases of extra low column effectiveness —a case at point being runs 147 and 148 of Fig. 1.

An extremely important attribute of the Straight-line Chart is the automatic check provided on the validity of test data and analyses of test samples in that, with properly stripped oil:

(1) Two or more sets of iso-butane and n-butane recovery points obtained with the same vapor-liquid tray loading and narrow range temperature changes on a given column must produce a common operating line.

(2) Two or more such operating lines obtained from different volume loadings under the same base operating conditions must converge at a common focal point.

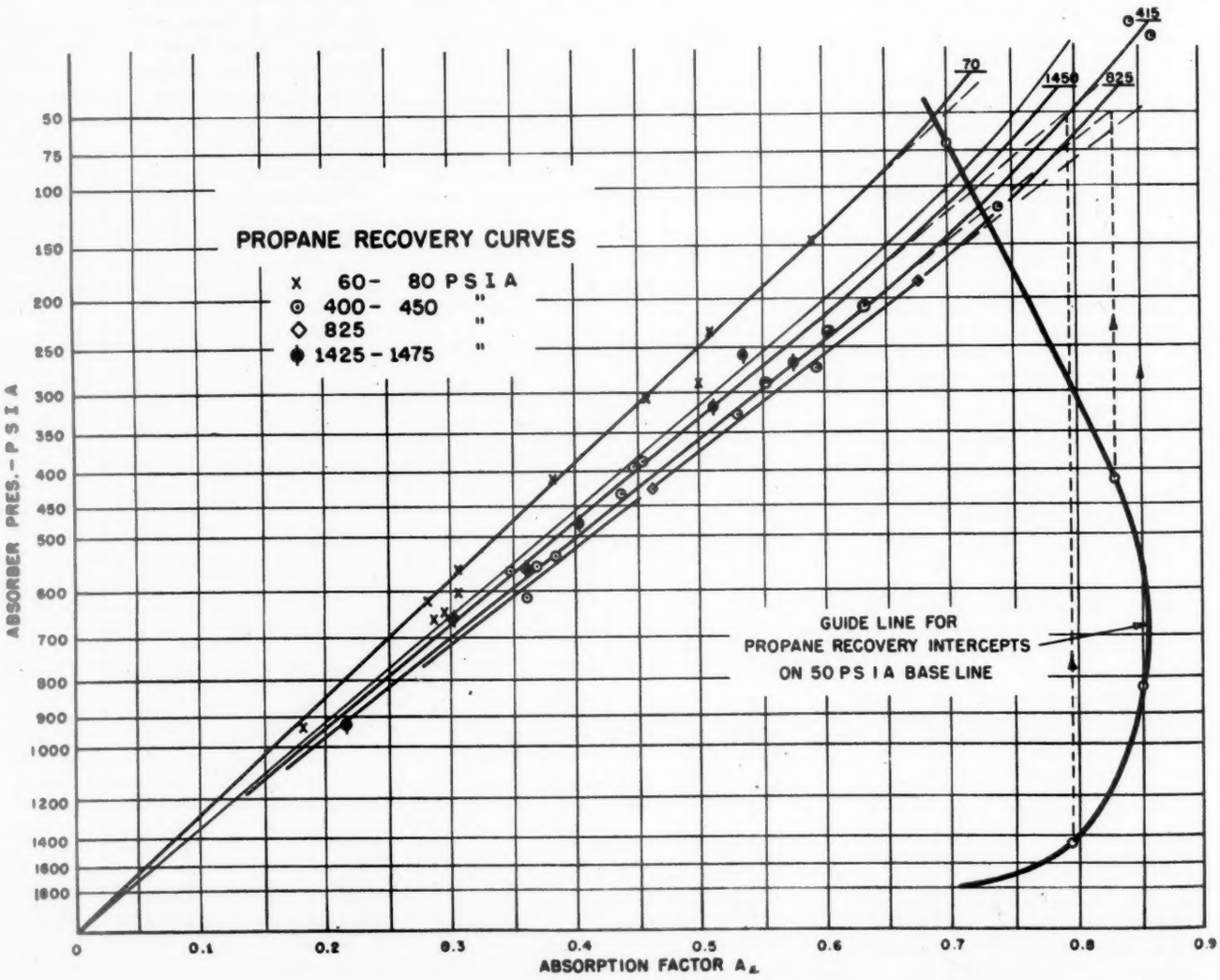
(3) This focal point must fall on the proper operating pressure line of the sub-grid.

(4) Associated propane recovery points must fall in their proper position on the Chart.

Obviously, even with the most careful test technique, all test data will not conform exactly with these Straight-line Chart standards. In justification for the stand that in order to be authoritative such data must reasonably so conform, we can state that:

To date, whenever we have found test data materially deviating from the Straight-line Chart standards, and have repeated the test, the second set of data has either conformed with said standards, or deviated as much or more from the first set of test data as either deviated from the Straight-line Chart standards. In other words, we have yet to find a consecutive series of test data consistently diverging from the above defined standards of the Straight-line Chart.

FIG. 7.



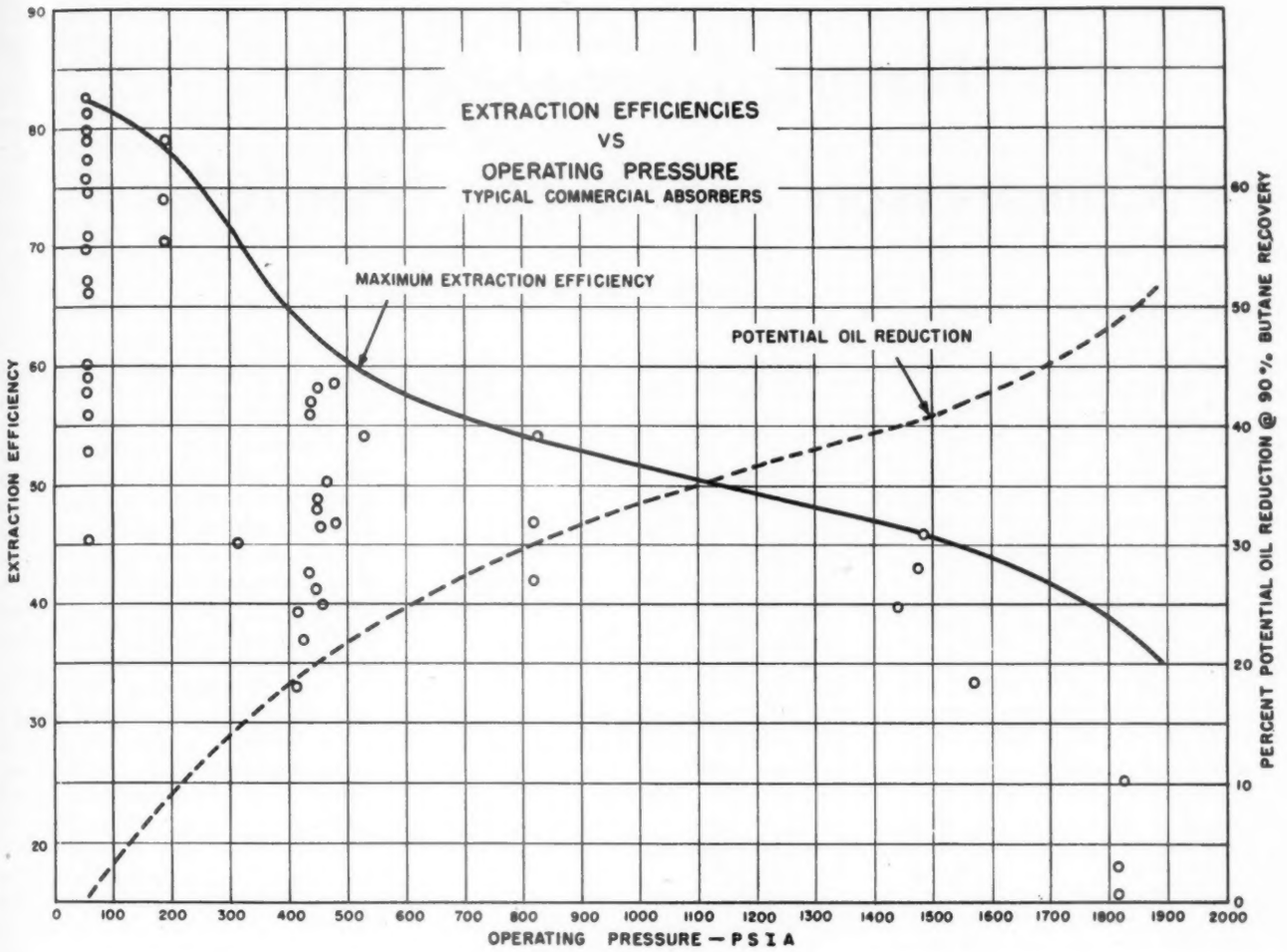


FIG. 8.

In this connection, we wish to emphasize that the extreme consistency shown by the plotted data of Figures 1-4 is the result of:

(1) Running extremely carefully controlled tests on well-equipped columns under excellent operating conditions.

(2) Charging extra large volumes of gas samples to the laboratory analytical columns whenever required.

(3) Repeating any key tests which failed to conform to the Straight-line Chart standards.

(4) Picking the best of such test data for the illustrative material of the figures.

Application of the Straight-line Chart analysis to a large number of special tests on a wide range of absorption columns during the last year has resulted in some rather striking generalizations concerning current commercial column efficiencies—which generalizations may be summarized as follows:

(1) All columns, irrespective of tray type or design, vary substantially in extraction efficiency with any substantial change in vapor and/or liquid loading.

(2) Such variations are much larger than generally appreciated over normally accepted ranges of column loading.

(3) The combination of vapor-liquid loading at which peak extraction efficiencies are attained varies markedly with type and design of tray layout.

(4) As a result, a very large proportion of all columns in actual operation today are not only operating well under the best attained efficiencies of the best columns in their particular class, but also well under their own particular "peak" efficiency.

(5) Many low pressure commercial columns operate at extremely satisfactory extraction efficiencies, whereas even the best of present day high pressure commercial columns operate at medium to poor extraction efficiencies.

(6) We have found nothing in our studies to indicate that the higher pressure columns cannot be designed to operate at extraction efficiencies approximating those attained with the best low pressure columns, and much to indicate that they can and will be so designed in the future.

The importance to natural gasoline plant economics of the above generalizations is indicated in Fig. 8 on which we present:

(1) A plot of Extraction Efficiency vs Operating Pressure for some 86 key tests on 30 different columns—with the boundary of best operation points being defined by a solid "Maximum Extraction Efficiency" curve.

(2) The saving in oil circulation requirements for 90 per cent butane recovery which would be effected over the indicated "Maximum Efficiency" operation if the present most efficient columns, irrespective of pressure, were capable of operating at the actually attained 82.5 per cent extraction efficiency of the best 60 psia columns.

When we realize that these potential savings apply only to the most efficient of present day commercial units, that probably less than 20 per cent of today's columns are operating at or near the indicated maximums, and that a great many commercial columns are operating far below the indicated "best industry" figures, the magnitude of the potential savings involved (either in the form of reduced oil circulation as per Fig. 8, or in added butane recoveries under conditions of maximum propane production) begins to be appreciated.

With steadily increasing demands for higher recoveries and greater fuel economies facing the Natural Gasoline Industry, attainment of at least a portion of the potential savings implicit in Fig. 8 would appear a "must" for the not-too-distant future—and it is our trust that the Straight-line Chart with its associated Extraction Efficiency factor "EE" will play an important role in this development.

In closing, we wish to acknowledge our indebtedness to all those companies and individuals who have so generously contributed facilities and data to this work, and without whose help the concept of a Straight-line Chart could never have been reduced to practical actuality.

★ ★ ★

Natural Frequencies of Compressors and Engine Manifolds*

EUGENE F. MURPHY

Noise, piping vibrations, and serious deviations from predicted compressor performance may all result if the natural frequencies of the compressor piping system equals some important component of the pressure wave set up by the intermittent "puffs" of gas passing through compressor intake or exhaust valves. Analogy between these pressure waves and electrical waves has long been known. The author has made use of this in developing a method for predicting the natural frequencies of proposed compressor piping systems. He has applied the method to piping systems experimentally studied by others; agreement has been found to be surprisingly close. His predicted frequencies were often within one per cent of the experimentally determined values.

The Problem. Builders and operators of reciprocating compressors for many years have been disturbed by a number of difficulties. Some are noise, piping vibration, low or unexpectedly high capacity, low efficiency, or serious periodic vibrations in speed, called hunting. Attempts to correct these difficulties in completed full-scale plants are expensive. Such disturbances appear to be due to resonance between the natural frequencies of the piping system or a portion of it and the fundamental or a harmonic of the pressure wave set up by intermittent intake or discharge of gas by the cylinder. Thus determination of the natural frequency of the piping system is necessary.

It will be recognized that these pressure pulsations within the piping may cause difficulties due to their effect upon the indicator cards or because of vibration of the piping itself as a Bourdon tube pressure gage and as a result of a change of momentum of the gas. It is emphasized that the *superimposed* oscillating component of pressure is studied, not the pressure drop due to steady flow through the system. An average pressure P_o throughout the system is assumed.

*Presented before the California Natural Gasoline Association this paper is based upon parts of a thesis submitted in partial fulfillment of the requirements for the degree of Ph. D. in Mechanical Engineering, Illinois Institute of Technology, Chicago 16, Illinois.

Methods of Attack. Direct calculation is possible for simple piping systems from the usual organ pipe theory, but more complicated systems cannot be calculated readily in advance of construction. Because of the complexity of the typical compressor or engine plant piping system, the labor involved in mathematical calculation is often unwarranted. The effect of a simple change of some quantity such as manifold volume can be determined only by repeating the entire calculation. The analogy to torsional vibration or to water hammer is apparent but not directly applicable. A direct experimental attack on a small-scale model is possible but difficult. Good indicator diagrams at speeds between 500 and 1500 rpm are rare. Measurement of the oscillating flow of gas is also difficult. The graphical method proposed by Warming[1] seems best adapted to quick solution of simple circuits but not to solution of complex circuits or especially to trial of many proposed alternatives on complex systems since a nearly fresh start must be made for each trial and a separate diagram is needed for each branch of any complex piping system.

An electrical analogy method was originally suggested by Dean L. M. K. Boelter, now at U.C.L.A., as a convenience in visualizing the problem. Experimental use of radio capacitors, inductors, and an oscillator at audio or radio frequencies appeared possible. The difficulties of changing wiring, the relative scarcity of readily variable accurate capacitors and inductors, the relatively large impedances of the connecting lines, and the possibilities of interference made this direct attack seem impracticable. Installation of an A.C. network calculator by the Armour Research Foundation of Illinois Institute of Technology made direct experimentation seem feasible.

The electrical analogy seemed desirable as a direct attack on an electrical network calculator of the type used for solving alternating current transmission line problems. In contrast to direct experiment, the electrical method permitted simple, safe, and accurate measurement by a single observer of the electrical potential difference or voltage, the current, and other quantities in a stable and easily adjusted system of any complexity. A given electrical circuit with definite numerical values actually represented a variety of acoustical systems, tending toward generalization of the problem. The use of an electrical analogy for an acoustical system is not original. Olson,[2] for example, presents a number of analogies. The use of the A.C. network calculator for *direct* experimental attack seems new.

The Analogous Circuit. An analogy between comparable systems depends upon the fact that behavior of each system is described by equations of the *same form*. The analogy used here depends upon substitution of electrical terms for the corresponding elements in differential equations derived for the acoustical system. The derivation made the usual assumptions of small pressure fluctuations from an average value, a continuous medium without shock waves, stiff and unyielding pipe walls, etc. The present analogy, as used experimentally, neglected the effect of resistance or damping upon the resonant frequency. Therefore, no attempt was made to

The Author

Born in Syracuse, New York, Dr. Eugene F. Murphy is a graduate of Cornell University with ME degree in 1935; after postgraduate work at Syracuse University received his MME in 1937; and did advanced study at Illinois Institute of Technology in Chicago, receiving a PhD.

From 1936 to 1939 he was in the engineering department of Ingersoll-Rand Company where he first became interested in prediction of natural frequencies of vibration of compressor and engine intake and discharge piping systems.

He is now Assistant Director for Research, Prosthetic and Sensory Aids Service, Veterans Administration, 252 Seventh Avenue, New York, and was formerly Assistant Professor of Mechanical Engineering, University of California.

predict actual pressure or velocity fluctuations.

The analogy between *lumped* mechanical, acoustical, and electrical systems is well known. The corresponding analogy in the case of a distributed system, while recognized, does not seem to have been used experimentally. Fig. 1 shows three simple, idealized, lumped systems. Friction or resistance and driving forces are neglected in each case. The respective differential equations are well known. Derivations are briefly outlined in the Appendix.

Several relationships are possible, but for convenience in visualizing the problem and in selecting the ranges of elements which are physically available, oscillating pressure (about an average pressure) has been replaced by alternating electric potential, and rate of oscillating gas flow or volume current by alternating electrical current. Then the inertia of the gas may be visualized as comparable to the inductance. The spring effect of a volume of gas (into which more may be packed by raising the pressure) is replaced by a condensor or capacitor, on which more electrical charge can be stored by raising the voltage.

Equations for long pipe lines with distributed parameters or properties are derived in different ways in various text books on acoustics and in a thesis by Rheinhart.[3] The final equations for motion show the same values for inertance and capacitance when compared with the equations for electrical transmission lines with distributed inductance, capacitance to ground, and resistance.

Electrical texts then show that the uniformly distributed parameters can be replaced, so far as the effects at the terminals are concerned, by lumped or grouped parameters arranged in pi- or T-shapes as shown in Fig. 1. For the pi-shaped lump, all the inductance in the line segment considered is gathered into a single inductor. All the distributed capacitance to ground is replaced by two capacitors, each half of the total distributed capacitance, connected from either side of the inductor to ground. Alternatively, the T-shaped lump splits the total inductance but combines all the capacitance. The two circuits are equivalent.

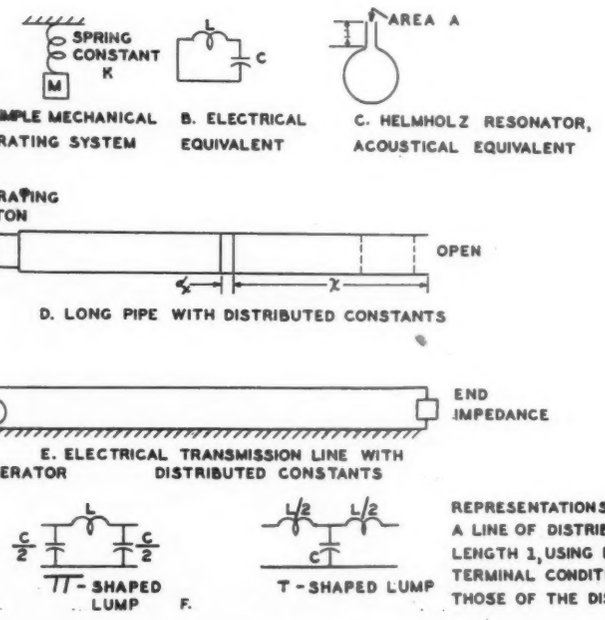
For adequate engineering accuracy the higher terms of the hyperbolic functions for the exact replacement can be neglected, provided the segment considered is less than 1/20th to 1/10th of a wave length at the frequency under consideration. Lumps 3 to 10 ft long are often suitable in dealing with engines or compressors.

Simplification of System. A consideration of the boundary conditions for the lumps shows that adjacent segments of a plain cylinderical pipe can be joined end to end. The adjacent capacitors may then be added and combined into a single capacitor. A similar process can be carried out at changes of cross-section, as from a small pipe leading into a header.

Certain components of predominantly one type of parameter, either capacitance or inductance, can often be represented by single lumps or even combined with the adjoining lumps. The acoustical inertance, analogous to electrical inductance, varies inversely as the cross sectional area of the pipe, while the acoustical (and analogous electrical) capacitance varies directly with that area. Thus, short sections of large diameter as compared to the rest of the system, such as manifolds or receivers, are analogous to nearly pure capacitors. If the small inductance is neglected entirely, the pi-shaped lump can be simplified to a single large capacitor which in turn can be added to the capacitors of the adjoining pi-shaped lumps to form as a single still larger capacitor. The total number of electrical units needed on the calculator is thus reduced. In general as many capacitors as inductors are necessary.

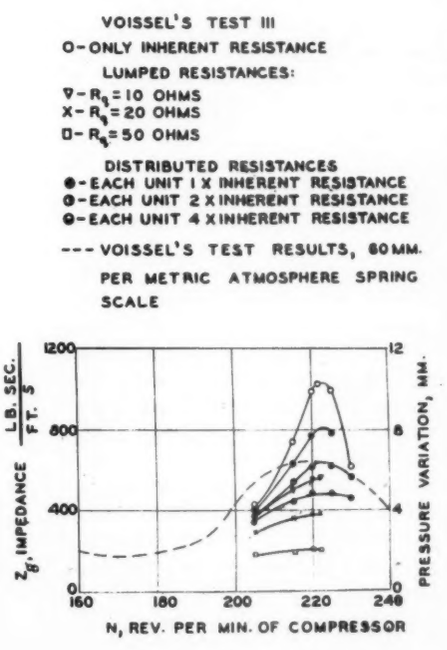
Termination of Line. An open pipe can be shown to correspond to an electrical short circuit, since pressure disturbances are immediately dissipated. At a capped or closed end the piping system is cut off, pressure can fluctuate, but no further disturbance is possible beyond that point. Correspondingly an open end of the electrical circuit, without connection between the line carrying the potential and the ground, prevents electrical current from flowing further but permits potential to exist between the line and ground and permits reflection of waves. An infinitely long line can be replaced by its "surge impedance" just as an infinitely long electrical transmission line. This impedance is

FIG. 1. Illustrating three simple idealized analogous lumped systems.



REPRESENTATIONS FOR PORTIONS OF A LINE OF DISTRIBUTED CONSTANTS, LENGTH 1, USING LUMPED CONSTANTS, TERMINAL CONDITIONS EQUIVALENT TO THOSE OF THE DISTRIBUTED LINE

FIG. 2. Effect of addition of resistance to an electric circuit.



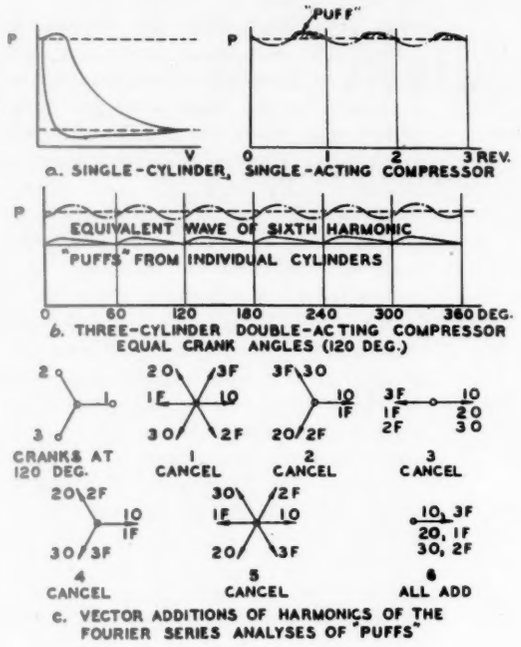


FIG. 3. Result of addition of components of pressure oscillation.

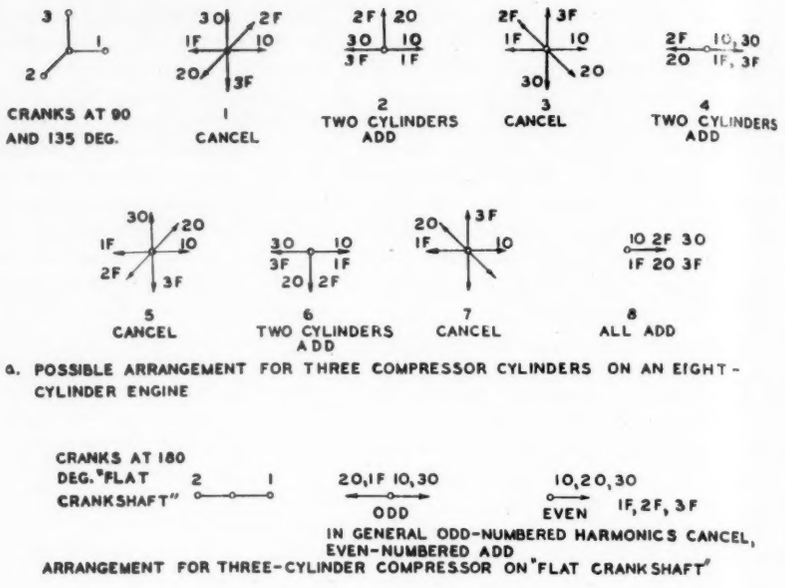

CRANKS AT 90 AND 135 DEG.
1 CANCEL
2 TWO CYLINDERS ADD
3 CANCEL
4 TWO CYLINDERS ADD
5 CANCEL
6 TWO CYLINDERS ADD
7 CANCEL
8 ALL ADD
a. POSSIBLE ARRANGEMENT FOR THREE COMPRESSOR CYLINDERS ON AN EIGHT-CYLINDER ENGINE
CRANKS AT 180 DEG. "FLAT CRANKSHAFT"
20, 1F 10, 30 ODD
10, 20, 30 EVEN 1F, 2F, 3F
IN GENERAL ODD-NUMBERED HARMONICS CANCEL, EVEN-NUMBERED ADD
ARRANGEMENT FOR THREE-CYLINDER COMPRESSOR ON "FLAT CRANKSHAFT"

FIG. 4. Result of addition of vector diagrams.

a pure resistance connected from the line carrying the potential to the ground. No reflections will occur from such an impedance since it is equivalent to a line through which the disturbance passes indefinitely without returning.

Resistance Neglected. In the calculations for most of the cases studied in the thesis and compared with practical experiments, resistance was neglected. A considerable number of cases, too numerous to report in detail here, included engine and compressor intake and discharge lines, some including surge chambers. The *natural frequencies* of the piping systems as determined by the electrical analogy coincided within one or two per cent with those determined experimentally on the actual piping systems.

To estimate, to a certain extent, the effect of resistance, electrical resistance was arbitrarily added in a circuit corresponding to Test III on a compressor intake by Voissel.[4] It will immediately be recognized that acoustical pressure drop varies as the *square* of velocity, whereas the electrical voltage varies only *directly* as the electrical current. The analogy thus does not truly hold for resistance, if a simple resistance element is used. (Since the experimental work for this paper was conducted, several multiplier systems have been described by Harder and McCann.[5] Their use, however, does not seem necessary for *this* purpose since for natural frequencies such satisfactory agreement was obtained with the complete neglect of resistance. No attempt was made to predict extent of pressure or velocity variation.)

As shown in Fig. 2 the addition of resistance, either as a lump at one point in the electrical circuit corresponding to the piping system or distributed throughout the circuit, merely lowers and flattens the resonance curve with only a slight downward shift of the natural frequency. As a matter of fact, addition of considerable resistance makes the electrical resonance curve more nearly resemble that obtained on the practical acoustical system.

Natural Frequency and Compressor Speed. The following section may be unnecessary for those familiar with methods for predicting torsional vibrations of crank shafts, a comparable phenomenon.

A Fourier series analysis might be made of the resultant pressure disturbances due to the train of "puffs" of gas or air in the pipeline immediately adjacent to the machine. The relative magnitudes of the fundamental and the various harmonics of the irregular "puff" due to one end of one cylinder will depend on many factors, such as piston action, relation of sizes of valve, pipe, and cylinder, valve opening speed and pressure at that time, etc. Fortunately, knowledge of the exact wave shape is unnecessary for practicable purposes.

As shown in Fig. 3 a crude picture may be obtained by considering the "puff" from the indicator card when replotted on a time basis.

If more than one cylinder end pumps into or from a given piping system, the appropriate harmonics can be added by vector diagrams, as in Figs. 3 and 4. The most serious disturbance will occur for resonance between the natural frequency in a given mode of vibration and a harmonic yielding the maximum vectorial sum of the harmonics of waves due to the "puff" from the individual cylinders. Less serious and often negligible vibration will occur for resonance between a natural frequency and other harmonics which add to lower values.

Comparison of Figs. 3 and 4 shows that the number of the harmonic whose vectors are parallel and in the same direction, and hence add directly, is *not* necessarily the sum of the number of cylinder ends. If the impulses are uniformly spaced, their sum equals the number of cylinder ends and indicates the number of the important harmonic. However, irregular firing orders or spacing of cylinders should be studied by means of the vector diagrams, as in Fig. 4. The relative importance of eight times the eighth harmonic compared to only twice the sixth harmonic for such a three-cylinder, double-acting machine will depend on the shape of the "puff." The engine crankshaft should be designed from this viewpoint as well as other considerations, such as firing order, stress, and torsional vibration. An estimate may often be obtained by superimposing arbitrary shapes of "puff" from the cylinder in their proper timing and noting the fre-

quency of the major ripple in the sum of the waves.

Impedance Calculation. For the acoustical system the properties of the gas at an average pressure P_o and temperature are presumed to be known. In the case of high pressure compressors the super-compressibility of the gas should be considered. The value for the ratio of specific heats should also be obtained for the pressure and temperature which will actually be encountered. Acoustical inertance and capacitance for the various segments of pipe line can be readily calculated, preferably in tabular form. Suitable sections or lumps are usually the length from cylinder to manifold, the complete manifold, and sections of 1/20th or even, with good accuracy, 1/10th of a wave length in the main discharge pipe. The wave length, of course, is that corresponding to the suspected harmonic of the operating speed of the compressor for which the vector diagram shows disturbance may occur.

The acoustical impedance Z_a is the pressure divided by the volume current in consistent units. The relationship between the acoustical and the electrical systems is then defined in terms of an arbitrarily chosen scale factor F_s.

For the particular calculator used, with an operating electrical frequency of 440 cycles per second, the inductive reactance was directly calibrated on the dial. The capacitors, however, are calibrated in microfarads.

Combining Cylinders. The process of adding units is shown in Fig. 5. In the box are shown first a three-cylinder compressor discharging into a manifold, then the same system with the manifold considered as a lumped volume or sphere with three parallel cylinders discharging into it, then an equivalent single cylinder discharging through separate passages into this sphere. It will be recalled that under the critical conditions at which serious resonance will occur, usually all the harmonics are in phase, and therefore the cylinders act as though they were one with all pressure waves in phase. The corresponding electrical networks are shown in the bottom of the box, although the very elaborate network corresponding to a distributed manifold is omitted because of lack of space. Around the top and right side of the box is shown the equivalent network. For a practical piping system the three parallel and equal inductors of the last circuit in the box are combined as a single inductor of value $\frac{1}{3}$ of any one of the three. The three parallel capacitors are combined as a single capacitor—equal to the sum of the three. Then the capacitors on the right side of the first pi-shaped lump and the left of the next are added and combined. The final result is an electrical system which looks as if it applied to a simple straight organ pipe. The numerical values of the first few units corresponding to the small pipes from cylinders to the manifold and to the manifold itself are not equal to the values for adjacent elements of plain pipe to the header.

This result indicates that a *generalized* system could readily be tested with systematic variation of the first few inductors and capacitors in comparison to the remainder to give the effect of variation in manifold size and volume. Some preliminary experiments of this nature were in fact performed very simply and rapidly.

Effect of Frequency, Speed Variation. The network calculator is operated at a constant frequency, say 440 cycles per second. The effect of varying acoustical frequency, corresponding to resonance with a new compressor speed, was obtained by varying the scale factor F_s and the inductive reactors on the calculator, X_c, leaving the capacitors at base values which were originally calculated for an arbitrarily chosen acoustical frequency. The inductive reactance varies as the square of the speed ratio while the scale factor varies directly with the acoustical frequency.

An alternative method varies the electrical frequency supplied to the calculator, leaving the inductors and capacitors at their initial setting. This method was also followed successfully. Consideration must be given to possible errors in the meters at variable frequencies for which the calculator was not originally designed.

Nature of the Calculator. The A.C. network calculator consists of calibrated and adjustable inductors, re-

FIG. 5. Development of a simplified wiring diagram, lumped manifold arrangement (14), 3-cylinder natural gas compressor.

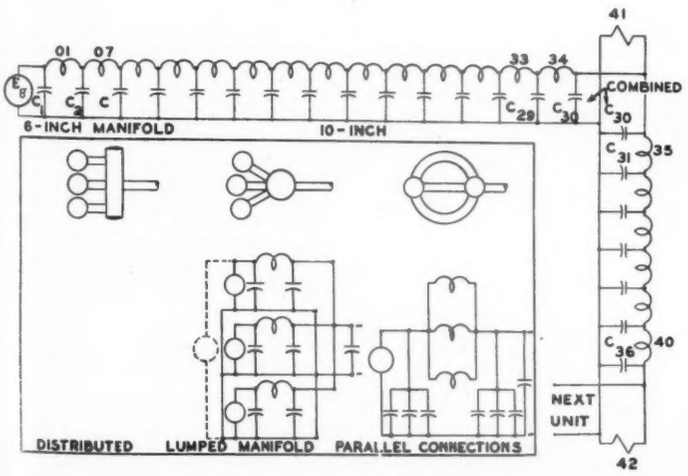
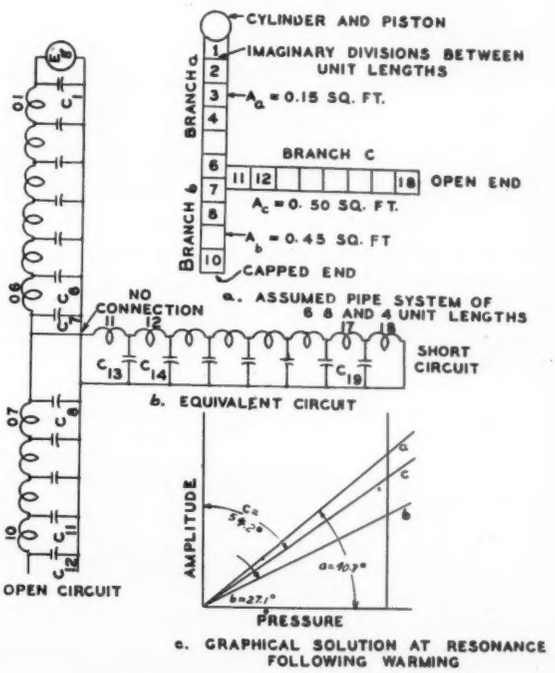


FIG. 6. Warming's graphical method for determining natural frequencies.



sistors, and capacitors, like enlarged radio parts. These can be combined in any desired arrangement by means of cord banks and plug boards which permit connection as simply as plugging a lamp into a base plug. The main metering desk is rapidly connected to any desired circuit element by small relays selected by push buttons on the desk, somewhat like dialing a telephone. The meters are operated by electronic amplifiers so that the drain upon the system and consequent distortion due to insertion of the meters themselves is negligible. They are in general more accurate and certainly are easier to use than equivalent acoustical devices, such as indicators or flow meters. They can be connected at any desired point in the system far more easily than pressure taps and orifice plates could be inserted in an actual piping system.

The generator used to represent compressors or engines is not a rotating device but rather a phase shifter or a set of coils. To determine *natural frequency* of a piping system only one generator was necessary. In this study a solution for steady state forced and natural vibration was sought. It is also possible, however, to apply transient potentials of arbitrary forms and to photograph the resulting wave forms on an oscillograph.

The highest value of impedance at the generator end, Z_g, was used as a measure of resonance with the applied electrical frequency and hence of the natural frequency of the equivalent acoustical system. The highest impedance indicated the greatest range of pressure oscillation for a given volume current oscillation applied by the fixed piston motion. The effect upon the pressure within the cylinder during valve opening in the actual acoustical system would then be a maximum. These observations were confirmed by the pressure-time diagrams in the studies by Voissel[4] on the intake to a compressor and by Farmer[6] on Diesel engines.

Because of the high first cost needed to obtain operating simplicity, few companies can afford to own a calculator. It is usually more practicable to participate in a cooperative agreement with other prospective users or to rent operating time on an existing calculator, of which well over a dozen are available in the country. The work reported here was done at Illinois Institute of Technology. In the near future U.C.L.A. will have a smaller, but adequate, calculator.

Results. The electrical analogy method was checked against reported natural frequencies of actual intake or discharge systems of compressors and engines containing air or exhaust gas, with temperatures from room to several hundred degrees. Tests included two and four stroke cycle engines and single- and double-acting compressors operating at 120 to 1200 rpm, in various combinations. The analogy method also agrees with Warming's graphical method shown in Fig. 6, both on his examples and on hypothetical cases.

A three-cylinder, double-acting compressor was studied extensively, but not included in the thesis. Tests on the calculator indicated severe vibration increasing from 1560 to 1830 vibrations per minute, with a peak vibration in a complex mode at the latter value. This was almost exactly six times normal compressor speed, 300 rpm. A vibrometer held against the discharge piping showed increasingly severe vibration of these same frequencies, always six times engine speed. Recent information, however, confirms a crankshaft arrangement of the eight-cylinder engine which would give 45-degree spacing, somewhat resembling Fig. 4, with harmonics from only two cylinders adding at six times

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engine speed, but all cylinders adding at eight times speed. One can only speculate, without further test, as to whether twice the sixth harmonic would exceed eight times the eighth. No tests were made on the calculator at frequencies corresponding to eight times normal operating speed range. Further study of this particular case is indicated, although the general method seems entirely sound.

For prediction of natural frequencies within two per cent, and usually less, only the inertance and capacitance of the system, calculated by essentially acoustical methods, need be considered. The discrepancy in pressure drop due to resistance, large variations of pressure compared to the mean, shock waves, the effects of bends, and the end effect of open pipes and sudden changes in pipe diameter may be neglected.

The analogy as used here does *not* yield quantitative values for pressure variations although they are qualitatively comparable to observations of relative pressure variations on the acoustical systems. Resistance, comparable to an orifice, lowers voltage (and pressure) variation, but resists direct as well as oscillating flow, wasting energy.

25,000,000 Housewives Cook With Gas

At the end of 1948, the gas utilities were serving 22,689,800 customers, including about 325,000 customers who receive LP gas or "bottled" gas directly from gas utility companies. In addition it is estimated that more than 4,500,000 customers are being served with LP gas in rural areas and other territories extending beyond the gas utility mains. Today nearly 25,000,000 housewives in the United States are "Cooking With Gas."

Either T-shaped or preferably pi-shaped lumps may be used to represent segments of piping. Some tests indicated that they may be 1/10 of a wave length with less than 1 per cent error in the resonant frequency.

Generalized Systems. An increase in shunt capacitance between the line and ground, equivalent to increase in receiver volume, *lowers* the natural frequency of the system but decreases the impedance, comparable to decreasing the pressure variations in a practical piping system with constant piston motion. Capacitance near the generator, or receiver volume nearer the piston, is more effective in producing these changes.

The addition of a capped branch pipe at any point along the line also lowers the natural frequency of the system and has greater effect when it is nearer to the compressor. The total of branch plus direct pipe exceeds the length of direct pipe alone needed for a given natural frequency.

Conclusion. It is thus seen that the natural frequency of a piping system can be predicted, resonance with the harmonics of "puffs" from the cylinders can be foreseen, and the effects of variation in manifold volume or pipe length can be predicted inexpensively in the design stage. Indiscriminate adding of receiver volume may well be dangerous because of lowering of natural frequency. Use of an orifice is wasteful and may also be dangerous, but an impedance—capacitance filter comparable to a low-loss muffler can easily be designed by simple experiments. Support by the industry of a concerted development of design criteria in the form of results on generalized system would seem worthwhile.

Acknowledgments. The author is deeply indebted to Dean L. M. K. Boelter of U. C. L. A., Dean W. A. Lewis and Dr. Lloyd Donnell of Illinois Institute of Technology, and

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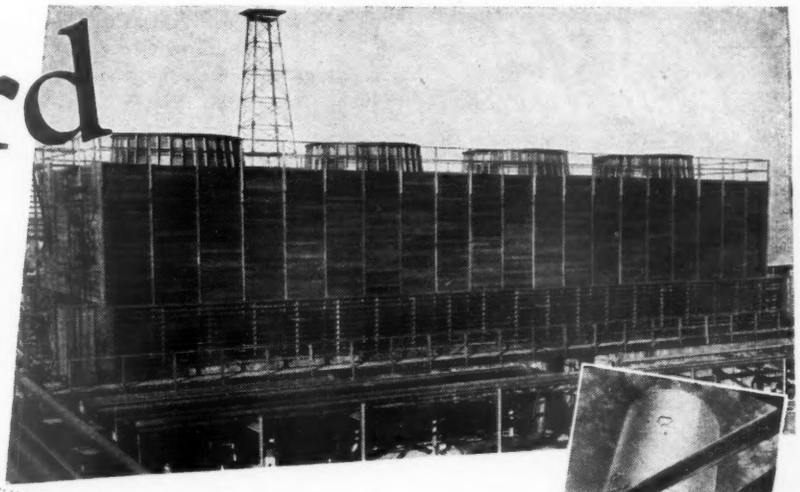
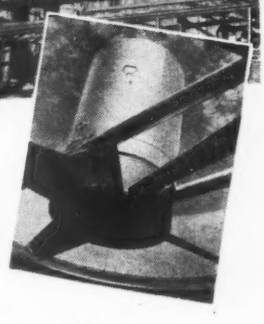
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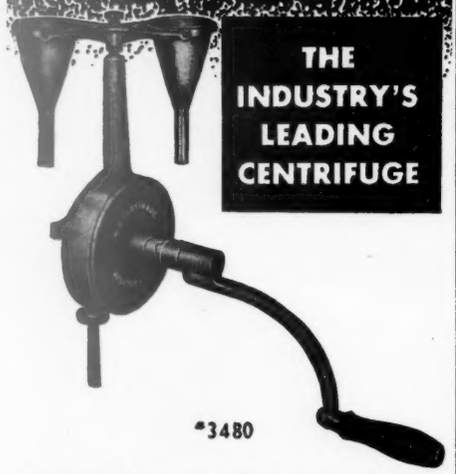

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APPENDIX

Differential Equations

With resistance and driving force neglected, the spring force applied to the mass in Fig. 1 equals the mass times its acceleration. The force F due to the spring, —kx or —k$\int$v dt, is directed back toward the neutral position. (If the system is not horizontal, the effect of gravity balances out if the neutral position is that of equilibrium with the weight on the spring.)

$$F = -kx = -k\int v\,dt = Ma = M\frac{dv}{dt}$$

$$M\frac{dv}{dt} + k\int v\,dt = 0 \quad . \quad . \quad . \quad (1)$$

Various electrical engineering tests show, usually from energy considerations, that in the simple circuit in Fig. 1:

$$E = L\frac{di}{dt} + \frac{1}{C}\int i\,dt = 0 \quad . \quad (2)$$

In the acoustical case of the Helmholz resonator, a plug of gas in the neck of a flask can be considered to be the mass. This then is the average density ρ_0 times the volume of the plug, or its length l multiplied by the cross-sectional area A of the neck. With considerable calculations based on the laws of thermodynamics, the restoring force due to the spring effect of the volume V of gas in the flask can be shown to be:

$$F = -P_0\gamma\frac{A^2x}{V} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Here P_0 = average abs. pressure

γ = ratio of specific heats and exponent for adiabatic compression; consideration should be given to any effect of super-compressibility.

x = displacement of the plug of gas.

Then in terms of the volume current I, or particle velocity times area, the usual form of Newton's Law or Eq. 1 can be rewritten as:

$$\frac{\rho_0 l}{A}\frac{di}{dt} + \frac{P_0\gamma}{V}\int I\,dt = 0 \quad . \quad . \quad (4)$$

Comparison of Equations 1, 2, and 4 shows the same general *form* if the meaning of the symbols is changed. This condition is termed *analogous*. (Thus, mx — b = 4 and ny — c = 6 are of the same form, linear equations, and might describe analogous conditions, but $x^3 - bx^2 - cx = 4$ would be an entirely different *form* of equation.)

Acoustical and Electrical Values

Comparison of Equations 2 and 4 indicates that certain acoustical properties, determined by the average properties of the gas and the dimensions, may be combined to give the equivalents of inductance and capacitance.

$$\text{Acoustical Impedance } L_a = \frac{\rho_0 l}{A} \quad (5)$$

$$\text{Acoustical Capacitance } C_a = \frac{V}{P_0\gamma}$$

. . . . . (6)

The particular network calculator used had inductive reactance units calibrated directly in terms of the inductive reactance X_c for the calculator frequency, f_c = 440 cycles per second. Then for a given acoustical case the base acoustical frequency corresponding to that calculator frequency is mN, or the number of the harmonic whose vector diagrams shows a maximum addition of the harmonics of the individual cylinders times the desired base engine or compressor speed.

$$\text{Inductive Reactance } X_c = F_s\frac{2\pi}{60}\,mN\frac{\rho_0 l}{A} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

It will be recalled that the scale factor F_s can be chosen at will. Integral values between one and ten were found convenient for all cases studied.

The capacitors were calibrated in microfarads, so:

$$\text{Calculator Capacitance } C_c = \frac{mN}{60F_s f_c}\frac{Al}{\gamma P_0} \times 1{,}000{,}000 \quad . \quad . \quad (8)$$

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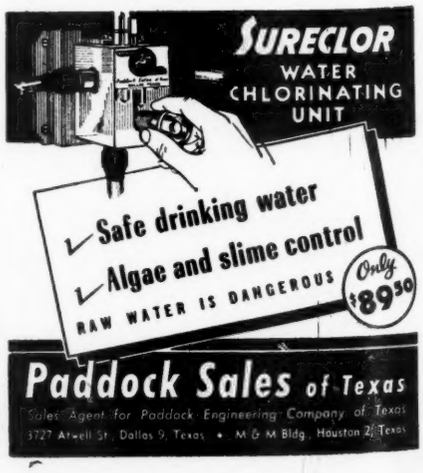

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Economic Sizing of Oil Pipe Lines*

F. C. WHITESIDE†

WHEN a new pipe line is under active consideration, several difficult factors present themselves for appraisal before the particular line design can get under way at all. They include the estimation of the peak production from the area, the estimation of the demand from the new area into the various refinery and consumer sections tributary to it, the estimation of the proportion of the total production that will move in the direction under consideration for the new line, and finally the estimation of what part of this movement the proposed line will be called upon to transport.

What size of line to lay into the new area then comes into the picture and this is always a difficult decision to make. The cost of oil transportation by pipe line decreases greatly with increased volume. The most economical line would therefore be the one just adequate to carry the peak throughput from fully developed production. Inadequate lines result in wasteful additions to the original plant as subsequent development occurs.

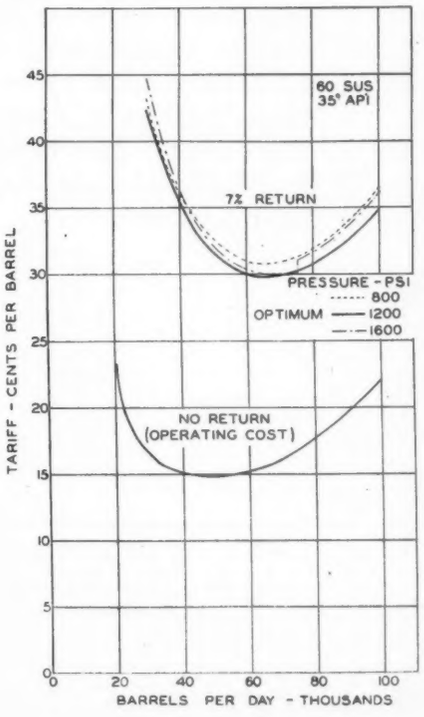
On the other hand the forecasters of the reserves in new discoveries are forced to limit their estimation of the producing area practically to proved acreage. Still, early in the development period, pipe line outlets have to be provided so that appropriation of funds for laying them partakes of the nature of appropriation of funds for the original exploratory expenditures and for leasing. That is, appropriations will be made that are based partly on faith in the area. There is some more basis than for the exploration costs in that oil will have already been discovered, but the volume of production for which transportation should be provided will not usually be defined for several years. With the best of planning, this is always a serious problem and requires the best application of business foresight. The seriousness of this situation can be emphasized when it is pointed out that practically every pipe line system of any extent built prior to the war was built too small. How this came to be can be understood by a retrospective glance.

In the early days of the oil business the unrestricted volumes from producing fields forced the feverish construction of pipe line outlets without adequate foresight in their planning. The high cost of overland transportation of oil by any means other than pipe lines made the pipe line rates of even such inadequately planned projects look cheap in comparison. The cheap appearing rates that still resulted in attractive profits provided inadequate economic compulsion for long range managerial planning. Whatever installations were built in most cases paid out all right, and it is unusual for owners to apply critical interest toward how an enterprise is designed and run when this enterprise is paying satisfactory dividends.

By far the greatest part of a pipe line system investment is in the lines themselves. In view of this and the natural difficulty in appraisal of the throughput from a new area at the start, and of the absence of economic compulsion to develop the basics of pipe line economics, it is easy to see why lines were practically always laid too small. This resulted in station spacings that were too close, operating costs that were too high, and subsequent wasteful loopings of the pipe line system as development progressed.

Trends long prevalent in the pipe line industry are now effecting a vigorous economic squeeze upon the transportation companies. Improvement in design and operating practices in some companies has injected heavier competition into the rivalry between lines transporting oil in the same general direction, which has driven tariffs downward just as persistently as wages and material costs have been rising. The most efficient pipe line system with the longest hauls and largest throughputs naturally have the lowest operating cost per barrel

FIG. 1. Tariff required for 12-in. line.

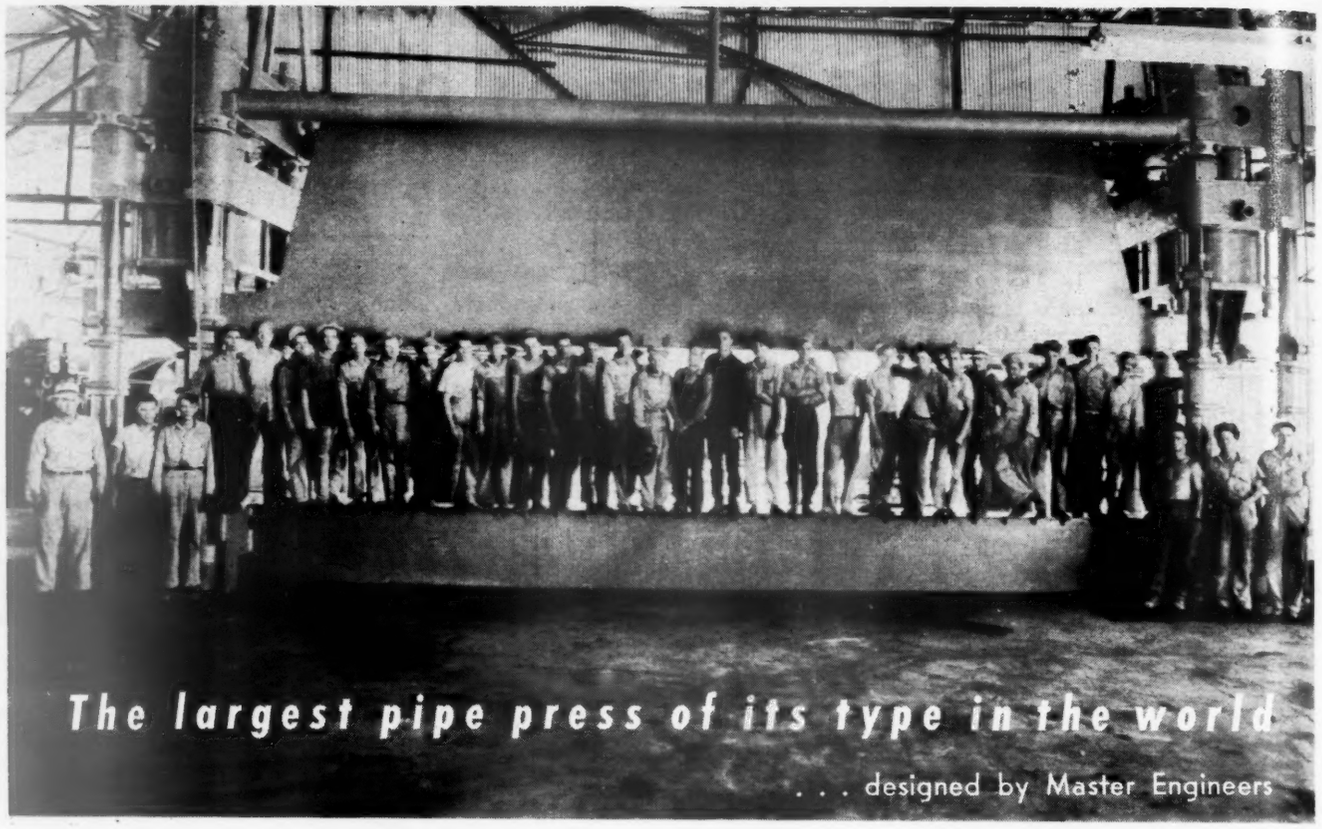


The Author

F. C. Whiteside received a B.S. degree in electrical engineering from Oklahoma University in 1931. Joined Oklahoma Pipe Line Company as a laborer immediately after graduation. Worked as telegraph operator, station engineer, timekeeper, warehouse foreman, district engineer, district superintendent's clerk, draftsman, and office engineer. In 1938, he was transferred to The Carter Oil Company as assistant employment manager, where he remained until 1941 when he joined the Standard Oil Company of Venezuela as safety engineer. Returning to the United States in 1943, he worked with the Plantation Pipe Line Company in Atlanta, Georgia, until joining Interstate Oil Pipe Line Company in 1945 as assistant to the division chief engineer. A year later he was promoted to division chief engineer and subsequently was appointed assistant chief engineer.

*Presented before The Pipe Liners Club of Tulsa, Tulsa, Oklahoma, April 18, 1949.

†Assistant Chief Engineer, Interstate Oil Pipe Line Company.



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mile. It is easy to see that pipe line systems in the same general service must meet the competition of the most efficient line.

Oil service in general the country over has been provided without radical variations in prices so that transportation costs anywhere will be affected by improvements anywhere else.

There are many papers that have appeared in recent years regarding trends in pipe line design. A great proportion of these articles describe the tendencies toward larger pipe diameters, thinner walls, higher tensile strength steel, higher operating pressures, longer station spacing, more effective and efficient pipe coatings, cathodic protection, etc.

To a lesser extent, papers have appeared that deal with improvements in station design. Pump and engine speeds are being increased, which allows the same output to be handled with lighter and cheaper equipment. The few large cylinders on the older type pumps are giving way to a greater number of smaller cylinders designed to give more even flow. Where oil viscosities permit it, the use of centrifugal pumps is coming into greater favor, which gives more freedom from surges.

With the practices in design in such a state of flux, it will be seen that settling upon an estimate of the expected throughput leaves many engineering investigations desirable in order to assemble cost figures for the optimum plant for the required service.

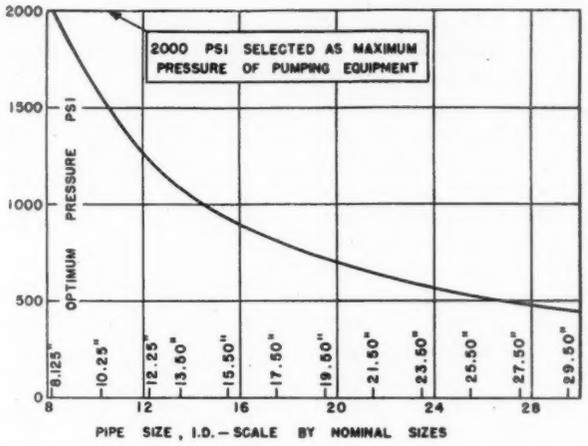


FIG. 2. Optimum pressure for 7 per cent return.

The economics and design of the line will be concerned with:

1. The length of the line.
2. The size of the pipe.
3. The minimum wall thickness at the low pressure end.
4. The tensile strength characteristics of the steel.
5. The safety factor to which the steel is stressed.
6. The price of pipe and equipment on location and the cost of construction.
7. Operating pressures.
8. Station spacing.
9. Volume of throughput.
10. Gravity of the oil.
11. Viscosity of the oil.
12. Temperatures encountered—averages and extremes.
13. Elevations along the line.
14. Operating practices and costs involved.
15. Desirable rate of return on investment.

The number of factors is so great and their interrelationship so complicated that full generalization of pipe line estimation data has always eluded complete acomplishment. The squeeze occasioned by falling tariff rates and rising costs dictates that complete economic evaluations be made. In the old days a rule of thumb said that an 8-in. line was a 20,000 bbl per day line and stations should be 30 to 35

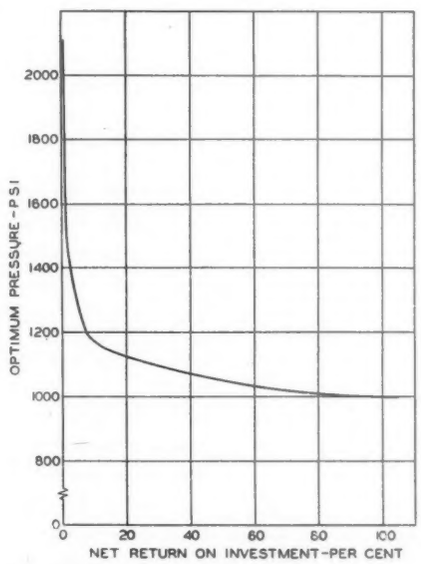


FIG. 3. Optimum pressure for varying return on investment 12-in. system.

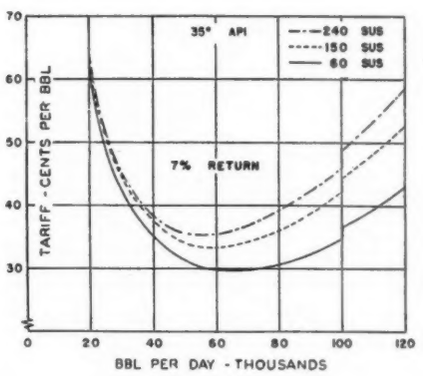


FIG. 4. Tariff required for 12-in. line at optimum pressure, 1200 psi.

miles apart. Recent improvements in materials, design practices, and operating procedures mentioned previously have upset the old customs, but uniformity has not emerged.

This paper proposes a method for presenting the general pipe line problem in such a way that many elements of a problem may be roughly estimated even while sitting at the conference table without the delay necessary to build the estimates up from the ground. It will also demonstrate many fundamentals in pipe line economics as of today which should bracket the line size within narrower limits, thereby reducing the number of proposals necessary to be worked out in complete detail.

Since all lengths of line, all sizes of pipe, operating pressures, etc., cannot be covered completely, the manner in which each was provided for is outlined below:

1. The length of the line was fixed at 1000 miles so that figures would be fairly applicable to any length except the very short, which always is a special case.

2. All sizes of pipe were covered from 8 in. to 30 in. inclusive.

3. Most recent construction practice, which calls for pipe walls telescoped to ¼ in. thickness on the receiving end, was followed.

4. API-5LX46 is considered preferable as no instances were discoverable of difficulties in welding it and the prices for this steel, having a yield point of 46,000 psi, are not greatly different from those required for the older Grade B at 35,000 psi yield.

5. The practice with respect to the safety factor to which the steel is stressed varies widely. *The ASA Code*

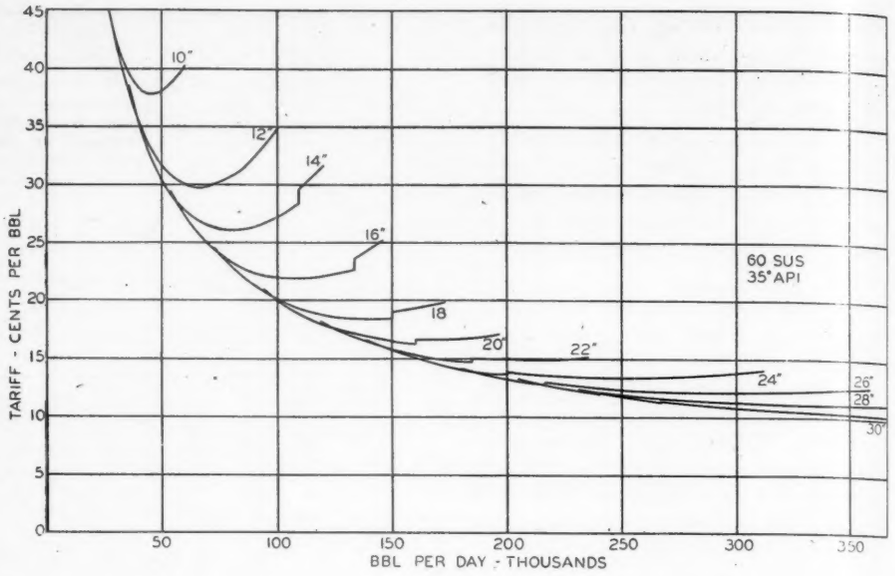
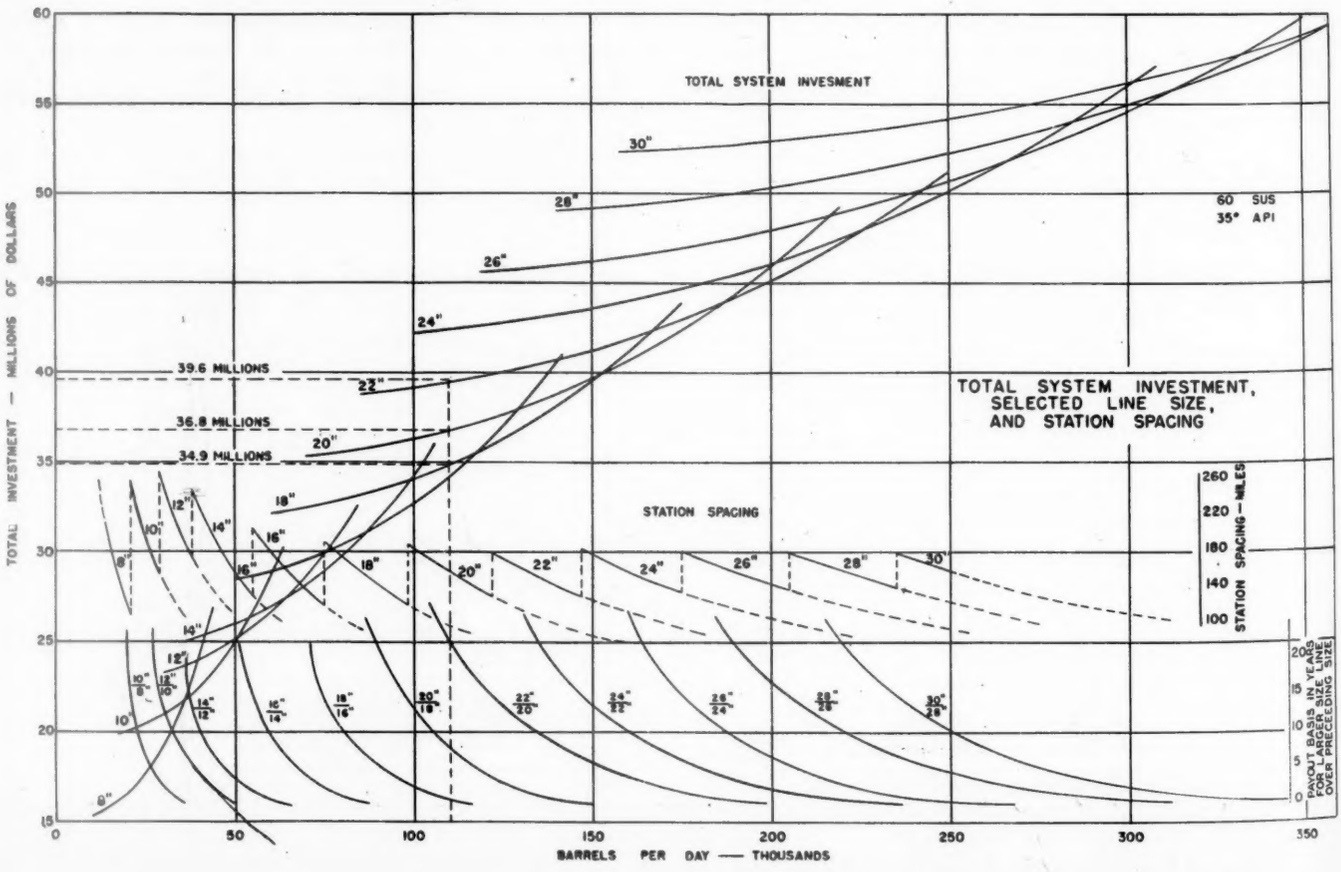


FIG. 5. Tariff required to earn 7 per cent net return on investment

FIG. 6. Total system investment, selected line size, and station spacing.


TOTAL INVESTMENT — MILLIONS OF DOLLARS
BARRELS PER DAY — THOUSANDS
TOTAL SYSTEM INVESMENT
39.6 MILLIONS
36.8 MILLIONS
34.9 MILLIONS
60 SUS
35° API
TOTAL SYSTEM INVESTMENT, SELECTED LINE SIZE, AND STATION SPACING
STATION SPACING
STATION SPACING — MILES
PAYOUT BASIS IN YEARS FOR LARGER SIZE OVER PRECEDING SIZE

for Pressure Piping calls for 85 per cent of the yield point. This has been used successfully in smaller lines. Most companies laying larger lines use something like 65 per cent of the yield. This study uses 85 per cent for Grade B, which also corresponds to 65 per cent for X-46 steel, so that these figures may be considered applicable to both these two conditions.

6. Pipe prices, freight, and construction costs were based on Oklahoma or nearby Mid-Continent areas as of June, 1948. Steel and freight have advanced about 10 per cent since then. Estimates of construction costs used have proved to be a little higher than actual jobs constructed since then so that the total costs in place should be just about right for the present time.

7. Operating pressures posed a particularly difficult job. By varying just the line size, operating pressure, and station spacing alone an infinite number of combinations would result. One of the three had to be fixed so that the relationship between the other two could be examined as the throughput varied. Obviously, neither line size nor station spacing could be fixed. If a way could be devised to show that an optimum pressure existed for each line size then that pressure could be used throughout for that line size.

The measure on which to base the optimum pressure determination is an interesting concept. The lowest operating cost will not measure it since this would ignore the excessive investment that might be required. The lowest investment would not indicate the optimum pressure since operating cost would be excessive in the cheapest system it was possible to build. The optimum pressure would set up a reasonable balance between the investment dollar and the operating dollar for the owner and deliver the transportation service to the public at the cheapest tariff rate. The fair return on the investment was selected as 7 per cent, which would give a payout of approximately 15 years.

Various pressures were then selected for each size of line and the tariff required to earn 7 per cent was calculated as the throughput was varied by varying the station spacing. These results were plotted on a graph for each size and the tariff line that dipped the lowest indicated the pressure that was optimum for that size of pipe.

Fig. I is a sample curve for this determination showing three pressure lines for 12-in. pipe. Although it was found that an optimum pressure did exist for all sizes above 8 in., it was not sharply defined and considerable latitude on either side could be allowed, with only a little variation in the tariff rate. Fig. 2 shows the optimum pressure for all the sizes. It will be noted that the optimum pressure for 8 in. was not indicated by the method. It proved to be too high for use with present pumping equipment.

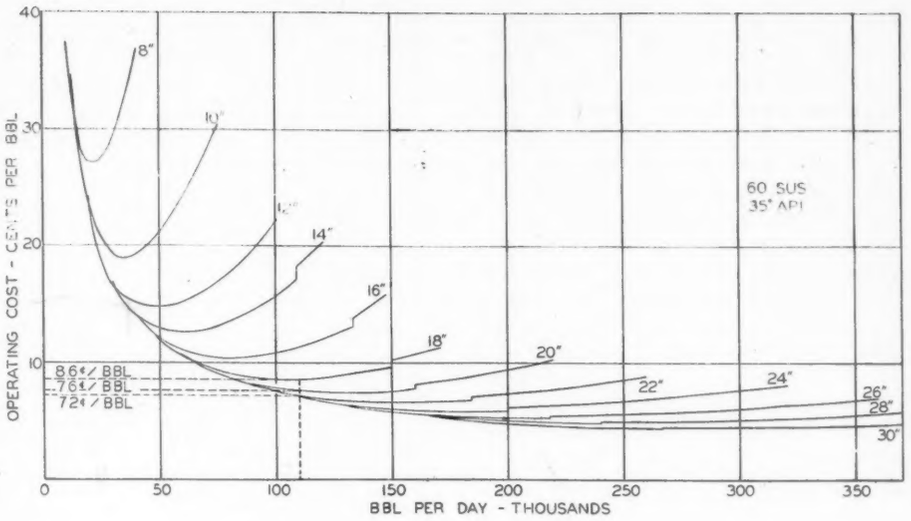


FIG. 7. Total operating costs.

It was discovered that with no return to the owner (operating cost only) the optimum operating pressure increased apparently without limit with all sizes because the condition that the owners should get a fair return on investment was removed. This led to speculation as to the behavior of the optimum pressure as the rate of return to the owners might increase shortening the payout period below the 15 years corresponding to 7 per cent as would sometimes be the case. This was calculated for 12-in. pipe out to 100 per cent return in one year. The results are plotted in Fig. 3. It will be seen that the optimum pressure drops from 1200 psi at 7 per cent return to 1000 psi at 100 per cent return.

8. Station spacing was varied as required to provide the throughput at the optimum pressure for each size as explained immediately above.

9. As the throughput is the basic variable it was allowed to vary

FIG. 8. Manner of determining line size.

Example: DETERMINATION OF THE PROPER LINE SIZE FOR A 110,000 BPD THRU-PUT OF 60 SUS CRUDE

OPERATING COST

	INVESTMENT FROM FIG. 1	¢ / BBL	$ / YEAR	SAVINGS AFTER 40% INCOME TAX	PAYOUT (YEARS)
18"	$ 34,900,000	8.6	$ 3,453,000		
20"	36,800,000	7.6	3,051,000		
Difference	$ 1,900,000	1.0	$ 402,000	$ 241,000	7.9
20"	$ 36,800,000	7.6	$ 3,051,000		
22"	39,600,000	7.2	2,891,000		
Difference	$ 2,800,000	0.4	$ 160,000	$ 96,000	29

SINCE THE 20" PAYS OUT IN 7.9 YEARS OVER THE 18" AND THE 22" REQUIRES 29 YEARS TO PAY OUT OVER THE 20", THE 20" LINE IS CONSIDERED TO BE THE APPLICABLE SIZE.

throughout the range required to encompass the 8-in. to 30-in. pipe sizes.

10. Gravity of oil was fixed at a representative median level, 35 deg API.

11. An average viscosity for the Mid-Continent area, 60 SUS, was used because of the impossibility of covering the ranges encountered in this important factor. Because it affects the problem greatly, two other sets of data were calculated, at 150 SUS and at 240 SUS. The effect of viscosity on the tariff of a 12-in. line at 7 per cent return and optimum pressure is shown in Fig. 4. Similar tariff lines for all sizes were plotted on a continuous throughput base to give the rates that could be expected for any quantity read at a glance, Fig. 5.

12. Design conditions were considered to be those found in Oklahoma and vicinity.

13. Elevation differences alone can present an unlimited number of conditions so that this study was forced to ignore its effect and consider the line profile as level.

14. Operating practices considered the crew as one man on duty at a time until the station size became such that more than two 1200-hp units were required to be operating to handle the throughput.

15. As explained under optimum pressure determination, 7 per cent was considered a fair rate of return on investment.

With these modifications of basic factors it was possible to present graphically the relationship between line size, station spacing, and throughput at the 7 per cent rate of return. Also can be shown which line size would be applicable with other rates of return corresponding to payout periods up to 20 years, Fig. 6.

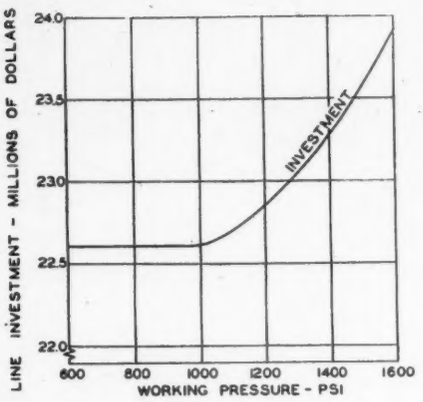


FIG. 9. Line investment for 12-in line.

The operating costs for the various systems can be plotted on a continuous throughput base in the same manner as the tariffs were shown, Fig. 7. The manner in which the appropriate line size for a particular quantity is established is shown in Fig. 8 from readings shown in the examples shown, Fig. 6 and 7. An interesting relationship with respect to minimum pipe wall thickness is illustrated in Fig. 9. The optimum pressure occurs only a little above the working pressure of the minimum wall thickness and the investment bears sharply upward at this point.

The demonstration of the existence and magnitude of optimum pressure is one of the interesting developments in this study. It will be seen that the size of line that should be employed is larger than used in most earlier installations and larger than in some of the recent ones. It is also interesting that as volumes increase, a larger size line becomes more economical before the minimum tariff is reached for the preceding smaller size.

This system of analysis can be made use of by any organization using their local conditions to develop the data. It is thought that the relationship between throughput and line size may not change very greatly as prices fluctuate since construction and operation costs should move in the same direction and in fairly comparable increments.

Most pipe line economics problems presenting themselves to a company that is a going concern will involve extension to or retirements from existing systems. This study will be of value here in visualizing the size of line to examine and the examination will be on what has come to be called an incremental basis. The cost of changes in plant will be balanced against what changes are caused in operating cost and in revenue.

Acknowledgment

Credit is acknowledged to George G. Hughes, Jr., and Norman E. Tilden of the Engineering Department of the Interstate Oil Pipe Line Company for the compilation of all the charts and data used in this study. ★ ★ ★

Technical Factors in Testing Pipe Line Coatings*

D. E. STEARNS†, M. W. BELSON†, and ROBERT H. LEE†

YEARS of work and experience with pipe line coatings have greatly improved their protective value; however, despite improvements in materials, machines, and techniques of application, the holiday continues to occur. Pipe line coating material must resist penetration by moisture, and must be electrically non-conductive in order to prevent flow of current between the pipe and the earth. The material, therefore, must be a dielectric, and its protective value is a function of its merit as a dielectric.

The minimum voltage at which adequate inspection may be made is determined by the mechanics of applying the coating, and by the thickness.

The minimum inspection voltage should be that which will jump an air path equal to the distance through the thickest section of the coating. A voltage impressed across an insulating wrap consisting of several different materials will divide itself across each layer as a function of the thickness of each layer, and in inverse proportion to the dielectric constant of the material. Air has a dielectric constant of approximately 1. Coal tar enamel has a dielectric constant of about 2. Thus, if 3000 volts be impressed across 1/8 in. of air and 1/8 in. of enamel, the voltage will be divided between the air and the enamel in a 2 to 1 ratio, with 2000 volts impressed on the air gap and 1000 volts on the enamel. In this instance the 1/8-in. air gap is sufficient to withstand the full 3000 volts without sparkover. Thus a proper test would not be applied to the coating. The voltage must be high enough to bridge any air gaps, such as small depressions or bubbles in the coating would represent, so that the full testing voltage is impressed across the material on which the test is desired. A voltage wave having a crest value of 10,000 volts will jump an air gap of 5/32 in. between suitable spheres. This same voltage will jump over three times this distance between needle points. Since commercially used electrodes have sharp edges or points, and the diameter of the wire in the electrode is small compared to the gap between electrode and pipe, and since, further, the pipe itself is rough, the sparkover distance between electrode and pipe is between that with needles and with spheres. Thus, on pipe coatings having a maximum spacing between pipe and electrode of 5/32 in., a minimum test voltage of 10,000 crest volts is satisfactory from the distance standpoint. By a similar reasoning, a minimum test voltage of 30,000 is required to inspect coatings that may be up to 1/2 in. thick. ★ ★ ★

*Excerpt from paper presented before National Association of Corrosion Engineers, Cincinnati, Ohio, April 11-14, 1949.

†D. E. Stearns Company.

Automatic Operation of Diesel Stations*

S. S. SMITH†

THE most significant change that has occurred in pipe line practice within the last few years is the transition from float tank operation to closed line operation. In float tank operation each station and its downstream line operates more or less as a separate system, increasing or reducing its throughput to match the accumulation or shrinkage of the stock in the float tank. Until a few years ago this sort of operation was current on the majority of crude lines.

With the advent of products pipe lines and the increasing necessity for segregation of special crudes for better refinery operation the closed line type of operation has become more prevalent. In this operation the whole line operates as a unit, all stations and sections of the line pumping at the same rate except where streams are added or withdrawn from the lines at gathering tank farms or terminal tank farms and, unless flows at each station are regulated automatically, it is difficult to maintain maximum rates or on the other hand control occasional excessive pressures. The minimum requirement for control in such a line is that each station be regulated automatically to maintain its suction pressure as low as is consistent with the type of pumping unit installed.

As demand for volume of products has increased and as the number of different types of products handled in pipe lines has also increased it has become more and more important to maintain completely automatic operation for reason of protection of specification of product, of maintenance of pipe line throughput, to guard against excessive and perhaps destructive pressures, and to maintain minimum pressures or packes when for one reason or another shutdowns are necessary. The purpose here is to describe complete automatic control of diesel-powered stations which have protection against every untoward happening and have been tested in operation sufficiently to prove their reliability and practicability. These units are in continuous service on an 8-in. line 250 miles long, partially looped, with a capacity of approximately 33,000 bbl a day on mixed products and with five stations between the original station and the terminal point.

The stations proper consist of 810-hp, 6-cylinder American Locomotive Company diesel engines, running up to 650 rpm connected to Farrell-Birmingham 1:6 ratio step-up gears and Byron Jackson 6-stage centrifugal pumps equipped with lubricated double mechanical seals. The requirements in design of these stations were:

1. The station should start automatically and operate through a predetermined warm-up period before picking up a maximum load.

2. The load pick-up should be gradual so as not to upset upstream or downstream station controls.

3. When on the line and after the warm-up and pick-up period, the station should function at line rate with a minimum suction pressure of approximately 50 psi and a maximum discharge pressure of 1000 psig.

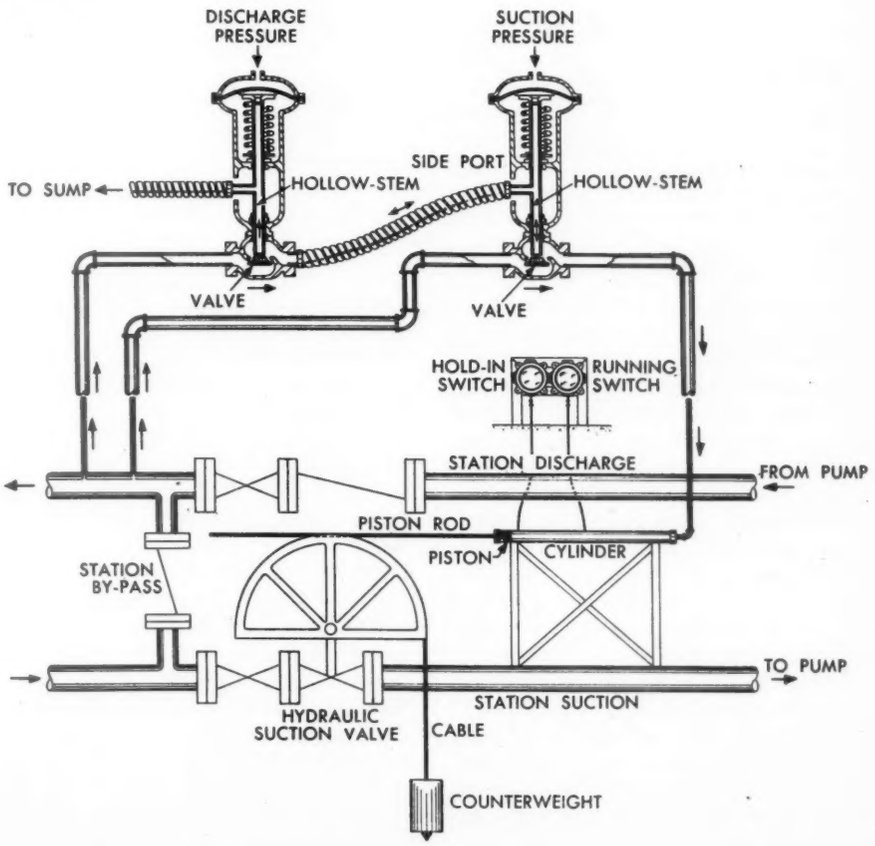
4. If mechanical trouble developed at the pump seals releasing vapor in the engine room, if bearings overheated in the pump, gear or engine, if the engine overheated or the bearings failed in the engine, the station should shut down automatically.

The primary basis for operation or non-operation of each station is taken to be the operating pressure of the pipe line through the station, which is a relatively accurate flow index and represents better than anything else the operating conditions on the line. With

FIG. 1. Schematic diagram of pilot controls for hydraulic suction valve.

DISCHARGE PILOT—On station start valve opens as pump discharge pressure rises to 550 lb admitting fluid from the line to maintain pressure on hydraulic suction valve cylinder through the stem port of the suction pilot. On station shutdown, as discharge pressure lowers, valve closes and port to hollow-stem opens to sump, relieving pressure in cylinder and permitting hydraulic suction valve to close under the action of the counterweight.

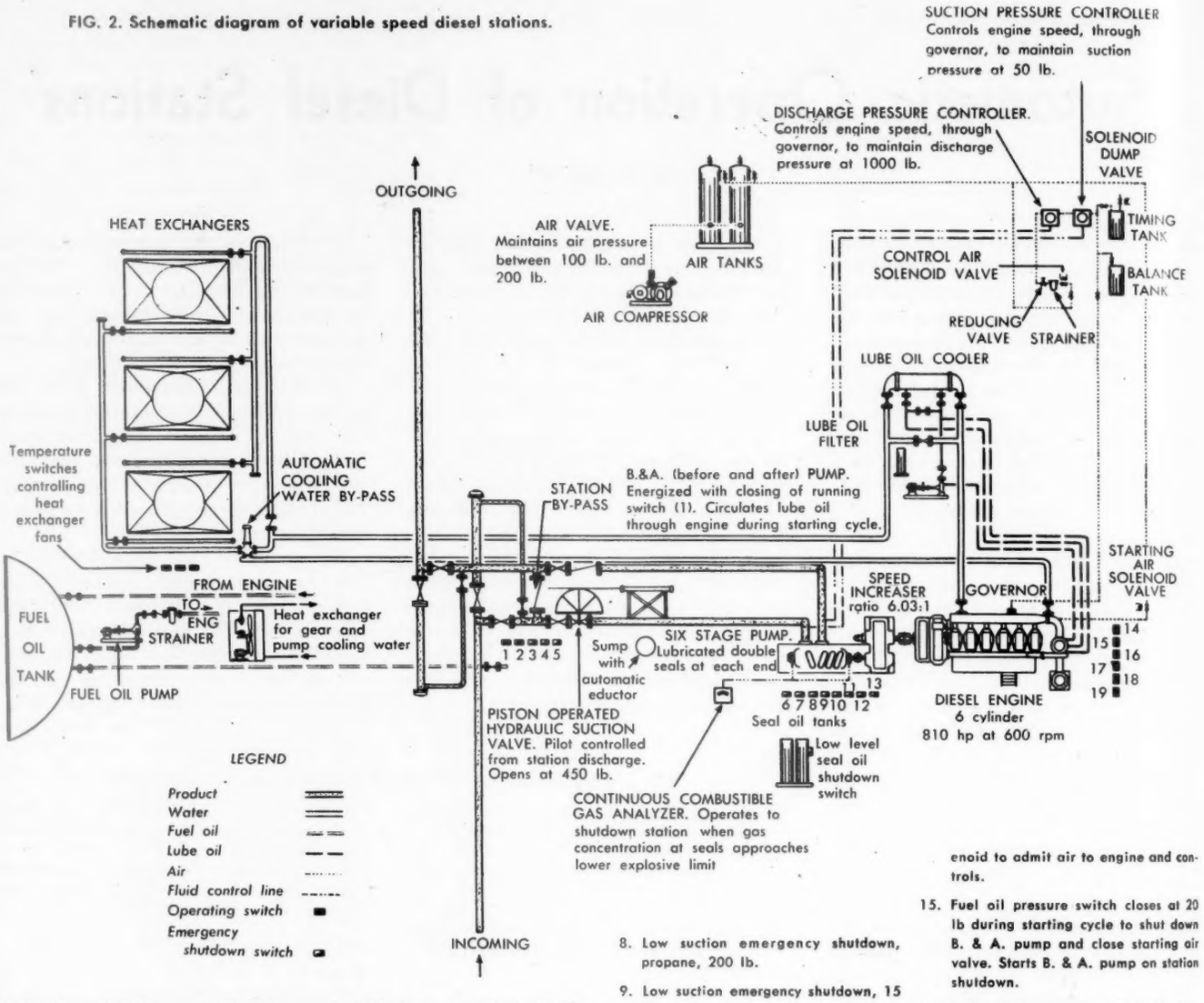
SUCTION PILOT—On station start valve opens at 450-lb line pressure to admit fluid to hydraulic suction valve cylinder. Side port closed to discharge pilot. As pump comes on and suction pressure is lowered to 50 lb, valve closes and port to hollow-stem opens to maintain pressure in cylinder from discharge pilot.



*Presented before the Petroleum Mechanical Engineering Conference of The American Society of Mechanical Engineers, Amarillo, Texas, under the title, "Automatic Operation of Diesel Pipe Line Pumping Stations," October 3-6, 1948.

†Manager, Products Pipe Line Department, Shell Oil Company, Inc.

FIG. 2. Schematic diagram of variable speed diesel stations.


SUCTION PRESSURE CONTROLLER
Controls engine speed, through governor, to maintain suction pressure at 50 lb.
DISCHARGE PRESSURE CONTROLLER.
Controls engine speed, through governor, to maintain discharge pressure at 1000 lb.
SOLENOID DUMP VALVE
TIMING TANK
BALANCE TANK
OUTGOING
HEAT EXCHANGERS
AIR VALVE.
Maintains air pressure between 100 lb. and 200 lb.
AIR TANKS
AIR COMPRESSOR
CONTROL AIR SOLENOID VALVE
REDUCING VALVE
STRAINER
LUBE OIL COOLER
LUBE OIL FILTER
Temperature switches controlling heat exchanger fans
AUTOMATIC COOLING WATER BY-PASS
STATION BY-PASS
B.&A. (before and after) PUMP. Energized with closing of running switch (1). Circulates lube oil through engine during starting cycle.
STARTING AIR SOLENOID VALVE
FROM ENGINE
TO ENG
SPEED INCREASER ratio 6.03:1
GOVERNOR
FUEL OIL TANK
STRAINER
Heat exchanger for gear and pump cooling water
SIX STAGE PUMP. Lubricated double seals at each end
Sump with automatic eductor
1 2 3 4 5
6 7 8 9 10 12 13
Seal oil tanks
Low level seal oil shutdown switch
DIESEL ENGINE 6 cylinder 810 hp at 600 rpm
14 15 16 17 18 19
FUEL OIL PUMP
PISTON OPERATED HYDRAULIC SUCTION VALVE. Pilot controlled from station discharge. Opens at 450 lb.
CONTINUOUS COMBUSTIBLE GAS ANALYZER. Operates to shutdown station when gas concentration at seals approaches lower explosive limit
INCOMING
LEGEND
Product
Water
Fuel oil
Lube oil
Air
Fluid control line
Operating switch
Emergency shutdown switch

1. Running switch. Closes at 450 lb to energize electrical control circuit. Actuated from hydraulic cylinder by opening of suction valve. Opens at 435 lb on station shutdown.
2. Hold-in switch. Parallels starting switch. Controlled from hydraulic cylinder and acts through timing relay in control circuit on drop in line pressure to hold station operative until line conditions are re-established.
3. Low pressure shutdown, 25 lb.
4. Low pressure shutdown, propane, 250 lb.
5. High pressure shutdown, 1050 lb.
6. Pump bearing temperature.
7. Pump gland temperature.
8. Low suction emergency shutdown, propane, 200 lb.
9. Low suction emergency shutdown, 15 lb.
11. Pump gland temperature.
11. Pump gland temperature.
12. Pump bearing temperature.
13. Gear bearing temperature.
14. Lube oil pressure switch, in starting circuit. Closes at 15 lb energizing solenoid to admit air to engine and controls.
15. Fuel oil pressure switch closes at 20 lb during starting cycle to shut down B. & A. pump and close starting air valve. Starts B. & A. pump on station shutdown.
16. Lube oil temperature switch. Controls B. & A. pump until lube oil temperature drops to 140° on station shutdown.
17. Engine bearing oil pressure.
18. Jacket water temperature.
19. Air pressure switch. Delays engine start if air pressure is below 100 lb.

comprehension of the requirements, the design of the station follows in order and the basic flow through the station is shown diagrammatically in Fig. 1, which neglects details such as scraper traps and main block valves.

Referring to this diagram, the flow into the station comes in through the station suction line and if the station is not operating goes through the station bypass and out through the station discharge line. As pressure rises in the station discharge line with the station not pumping, line pressure is admitted to both the suction and discharge pressure pilots, which are set at pressures that correspond to the hydraulic characteristics of the section of line that the individual station serves. For convenience of discussion definite pressures are shown on the various valves' settings, but it will be understood that these are varied as the operating characteristics of the line dictate, and it is only for convenience of description that specific pressures are assigned. As the line pressure rises to 450 psi the suction pilot opens admitting high pressure fluid from the station discharge line through the opened valve to the cylinder of the hydraulic suction valve. This drives the piston and piston rod across the quadrant of the suction valve, lifting the counterweight and opening the valve. The opening of the suction valve pressures the station and connects it to the line ready for operation. Other control circuits are involved in this operation but for the moment assuming the station becomes operative, pressures on the suction side will decrease and on the discharge side will increase. As they decrease on the suction side the suction pressure pilot closes and opens the upper valve through the side port into the discharge pressure pilot, which has opened as the discharge pressure of the station rises.

In this manner, after the station becomes operative the running or shutdown control is transferred from the suction pressure pilot to the discharge pressure pilot, and any time the discharge pressure falls below 550 psi this pilot closes, opens its upper side port and drains liquid from the hydraulic suction valve cylinder, permitting the counterweight to close the

valve, thus isolating the station from the line. The purpose of this dual pilot setup is to permit the station to come on the line at pressures that can be attained by upstream pumping stations and to hold the station on the line until the discharge pressure has been pulled down to a point where the station should go off the line. The dual arrangement of the pilots permits the starting and shut-down pressure points to be independently adjusted and avoids any difficulty due to lag in the pilots requiring that the line pressures be pulled lower than starting pressures in order to stop the station.

Station Control

When the suction valve is open and the piston is at maximum travel outward in the hydraulic cylinder, a port is uncovered, which admits high pressure line fluid to two Mercoid switches, designated by their functional names of running switch and the hold-in switch.

Now refer to Fig. 2, which is a schematic diagram on the whole station and control circuit. When the running switch closes by admission of fluid from the suction valve cylinder a circuit is energized to operate the B and A pump, which pumps lubricating oil from the engine base through the lube oil coolers and through thermostatic controlled heaters to circulate warmed oil through the engine before the engine starts. As the B and A pump operates and builds pressure in the engine lube oil circuit, it actuates Mercoid No. 14, which is a lube oil pressure switch, and this switch closes to energize a solenoid valve to admit starting air to engine. The engine now turns over under starting air until it dieselizes and picks up speed, resulting in an increase of fuel oil pressure from the fuel oil pump on the engine, which in turn opens the circuit to shut down the B and A pump, closes the starting air valve, and admits reduced pressure air to the engine controllers.

At this stage in the starting cycle the engine is rolling at idle speed, and the main pump is creating about 200-psi differential, pulling down the suction pressure by about 100 psi and increasing the discharge pressure in like amount. This affects the previously mentioned transition of master control from the suction pilot to the discharge pilot. Now, as per previous statement, it is desired to operate the engine for a short warm-up period before picking up full speed and getting the station completely on the line. All the line throughput is now going through the pump, the engine is very lightly loaded at about 100 hp and is turning over about 250 rpm.

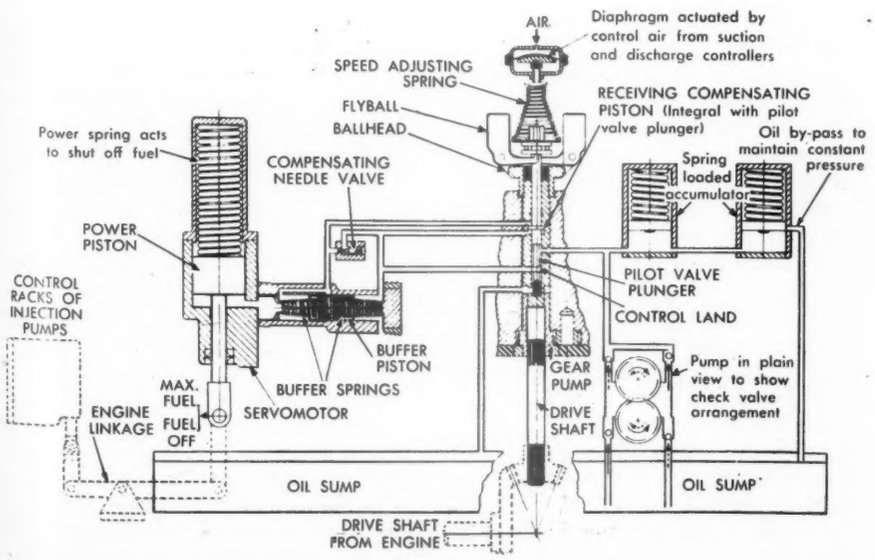
Air is admitted to the two air controllers, whose controlled pressure builds up slowly in the timing tank and the balance tank, and this pressure rises through about a 5 min period to approximately 10 psi. From this pressure point on, the air being admitted to the governor mechanism gradually picks up the speed of the engine until either maximum speed or controlled conditions on the line are arrived at somewhere around 20-psi air pressure on the governor. The governor mechanism is shown in somewhat deleted fashion in Fig. 3, which is an overly simplified diagram of the Woodard speed governor, which handles the idle speed, the maximum speed, and any intermediate control speed as directed by the air controllers by hydraulically controlling the fuel pump rack on the Alco diesel. This governor incorporates compensating principle and provides stable governed speed on the engine through normal changes of controlled speed and should require no further description in this discussion.

Referring back now to Fig. 2, it will be noted that the discharge and suction pressure controllers are connected in series so that either one may reduce air pressure to the governor and slow the engine. These are set respectively at 1000-psi discharge pressure and at 50-psi suction pressure. They are simple proportional air controllers, single compensated, manufactured by Mason Neilan and equipped with restriction coil and balance tank to reduce the speed of their operation to the requirements of normally slowly changing pressures in the pipe line system.

In this running description of the sequence the point is now reached where the station is on the line under full control, operating with suction pressure of 50 psi and sufficient discharge pressure to pump all the arriving fluid to the next station, or at a discharge pressure of 1000 psi and sufficient suction pressure to slow down the incoming line to the rate the station can pump to the next downstream station. At this point in the operation the engine is generating heat to its cooling system and as the water temperature rises the automatic thermostatic controlled bypass closes, directing the cooling water stream through the air-cooled heat exchangers. With a temperature rise to 140 F the first cooler is thermostatic controlled to operate its motor-driven fan, and with further increases in temperature to 150 F and then to 160 F, the second and third cooler fans also thermostatically start and operate. A separate cooling water system circulates water over the gear and pump, the motor circuit for this air-cooled heat exchanger being energized by the main operating circuit of the station.

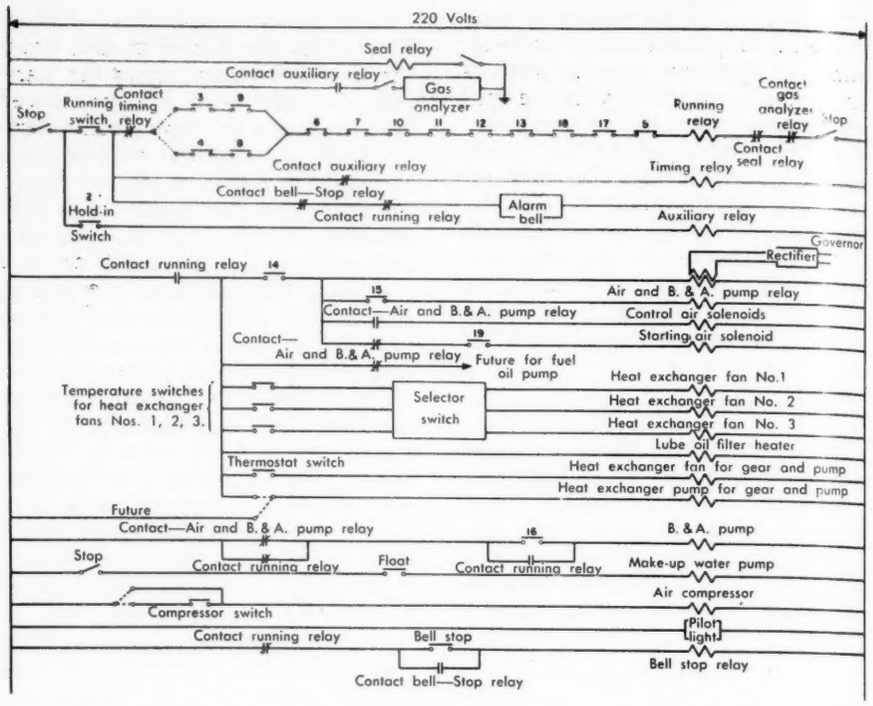
By reference to Fig. 4 it will be seen that any high bearing temperature, gland temperature, or pump case temperature can interrupt the running circuit of the station and shut down the engine and pump, as can also unduly low pressures on the suction side of the station or high pressures on the discharge side of the station. Here it is to be noted, too, that separate pressure switches are provided to take care of the high pressures required when pumping propane through these stations, at which time pressures can not be allowed to fall to vaporization points of the liquid propane at its pumping temperature.

FIG. 3. Schematic diagram of governor.



Conventional practice in the past has been to separate diesel engines from inflammable liquid pumping units by fire walls or other means of assuring vapor-free engine rooms. In these diesel stations a different approach has been made to this problem. The 6-stage Byron Jackson pumps are equipped with double mechanical seals with first stage pressures applied to balance tanks containing lube oil that feed to the space between the dual seals. In normal operation any external leakage through the outer seal is lubricating oil, and any leakage through the internal seal is lubricating oil from the inner seal space to the product contained in the pump. As an additional safeguard against vapor leakage into the engine room a gas analyzer is run continuously, analyzing air drawn from a point immediately adjacent to each seal; thus if a vapor concentration does develop at this point the gas analyzer immediately detects it and operates a relay in the running circuit to shut down the station. By these dual safety measures the engine rooms are made safe for operation of diesels and pumps in the same room, resulting in operating and maintenance convenience and in considerable saving of space and construction costs.

FIG. 4. Electric diagram of variable speed diesel stations.



3. Low pressure shutdown, 25 lb.
4. Low pressure shutdown, propane, 250 lb.
5. High pressure shutdown, 1050 lb.
6. Pump bearing temperature.
7. Pump gland temperature.
8. Low suction emergency shutdown, propane 200 lb.
9. Low suction emergency shutdown, 15 lb.
10. Pump case temperature.
11. Pump gland temperature.
12. Pump bearing temperature.
13. Gear bearing temperature.
14. Lube oil pressure switch.
15. Fuel oil pressure switch.
16. Lube oil temperature switch.
17. Engine bearing watchdog.
18. Jacket water temperature.
19. Air pressure switch.

Shut-Down Sequence

Normally, these stations operate continuously at close to maximum capacity. However, at regular periods when products pumped through the line indicate that throughputs may be reduced, stations are shut down, inspected, and any necessary repairs or adjustments are made.

The shut-down sequence is approximately the reverse of the starting sequence. When throughputs in the line are reduced the discharge pressures at all stations fall, accordingly, and when the pumping pressure at the station falls to the pressure at which the discharge pilot is set (Fig. 1), this valve opens its upper port to sump and fluid flows from the hydraulic suction valve cylinder, permitting the counterweighted suction valve to close. As the piston in the cylinder travels toward the closed position, the ports to the running switch and the hold-in switch are opened and the liquid pressure in the switches drains to sump. As these running switches open they also open the main running circuit in the control board, and the control air is cut off of the governor, thereby stopping the fuel to the engine, consequently stopping the engine. As the fuel oil pressure at the engine drops to 20 psi the B and A lube pump is again started to circulate oil until the engine has cooled to 140 F, at which time the B and A pump shuts down and the station is completely inoperative. In the meantime, as the engine is stopping, the electric circuits to the engine water heat exchangers and the gear and pump cooling water heat exchangers have been opened, and the fans of these coolers have stopped. Also, as the air was cut off to the engine governor it was also cut off to the air controllers, and the air contained in the time tank that gave the delayed circuit is reset for the next start.

If instead of the normal stop, which has just been described, there occurs an emergency in the station such as a hot bearing or any other untoward incident, the pressure or temperature switch which is affected immediately opens and the whole stop sequence is immediately initiated. In this case the line pressure will fall because the pump is no longer on the line, and again when the line pressure comes down to the set point of the discharge pressure pilot, this pilot will open and the main suction valve will close, isolating the station from the line. In all cases of automatic shutdown the station is isolated on the discharge side by a single-seated, piston-guided check valve.

Summary

This description of the diesel stations, although obviously condensed and omitting a number of items of control, delineates the methods used to accomplish the four major objectives. The automatic station start is accomplished through the suction valve and its associated electric controls, and the automatic warm-up period is obtained by the delayed action of the air controls. The objective of operation control after the stations are on the line is accomplished by the dual air controls and hydraulic governor setup, and these functions are consummated with very close accuracy without surging or hunting. The fourth objective of stoppage of the stations in case of mechanical trouble is accomplished by the bearing watchdogs and their associated electric controls, the temperature and pressure Mercoids, which function in case of any uncontrolled temperature or pressure, and the continuous analysis of vapor content of samples taken at the pump seals that, in conjunction with the automatic shut-down features, prevent the stations' operation in case of any seal failure or liquid or vapor leaks at the pump. ★ ★ ★

Graphic Method for Dispatching Operation On a Products Pipe Line System*

ALLEN BAXTER†

Abstract

This paper is a description of a chart used for determining and showing the location of the various grades of petroleum products that move through a pipe line system that regularly transports 13 grades and brands of products from refineries in Philadelphia to sales terminals throughout Pennsylvania, New York, and Ohio. It is also an explanation of the ways in which a graphic method is used to control and aid dispatching operations in general.

In the period immediately following World War II and the return of the Keystone Pipe Line and Buffalo Pipe Line systems to the normal distribution of petroleum products from refineries located in the Philadelphia area to terminals throughout Pennsylvania, New York, and Ohio, these systems shared the industrywide condition of greatly increased demands upon facilities that had remained unchanged since before the national emergency (Fig. 1).

The volume of products tendered by shippers soon approximated what it would have been had there been no war and normal annual sales increases had continued through the war years. The pipe line system—including pumping stations, trunk lines, and delivery facilities—of course, was loaded to capacity, and more, before new equipment could be obtained and installed. The solution of this throughput problem by the purchase of War Assets Corporation's surplus property and the lock-stock-and-barrel removal of the pipe line and pumping stations of the Greensboro, North Carolina, to Richmond, Virginia, extension of Plantation Pipe Line would be a fitting subject for another time, but is not our particular interest now. It is sufficient to say that some of the pipe was used for loops on the Keystone system, and the four pumping stations were re-erected on our line to Buffalo, New York. Other equipment purchased from Southwest Emergency Pipeline was installed throughout Pennsylvania, where needed. In this manner the capacity of the entire system was increased so that it can now move all the product oil tendered (Fig. 2).

The erection of larger storage tankage by the shippers, however, was not so rapidly achieved. Especially in the case of furnace oil, the demand had grown tremendously since prewar; yet the terminal tankage was unchanged. In some areas where furnace oil had not been supplied through a pipe line terminal, there was now a volume required in the immediate locality that made it imperative for the shipper to have storage for this grade, even at the expense of gasoline or kerosine storage. Several shippers at different locations required diesel oil shipments as separate movements from their furnace oil tenders. One shipper obtained from the purchasers of the Big Inch lines the tank farm at Phoenixville, Pennsylvania, and now tenders more than a million barrels of furnace oil to this terminal for seasonal storage of this product to be moved during the same period that the gasoline load is at its peak. And so on and so forth, the complications of the dispatching operations were multiplied over and over.

At that time we were using the same system for control of our dispatching operations that was used when batching procedures were inaugurated on our system in 1932. This was simply an hourly accumulation of the amounts delivered from the system ahead of a given batch. In conjunction with this tabulation, we posted a glass-covered scaled schematic plan of the system to show the location of each batch every hour. This chart also indicated which terminals were receiving, their receiving rate, the grade and consignee of the delivery, the rate in various sections of the system, batch

*Presented before the Annual Meeting of the American Petroleum Institute, Chicago, Illinois, November 8, 1948.

†Keystone Pipe Line Company, Philadelphia, Pennsylvania.

FIG 1.

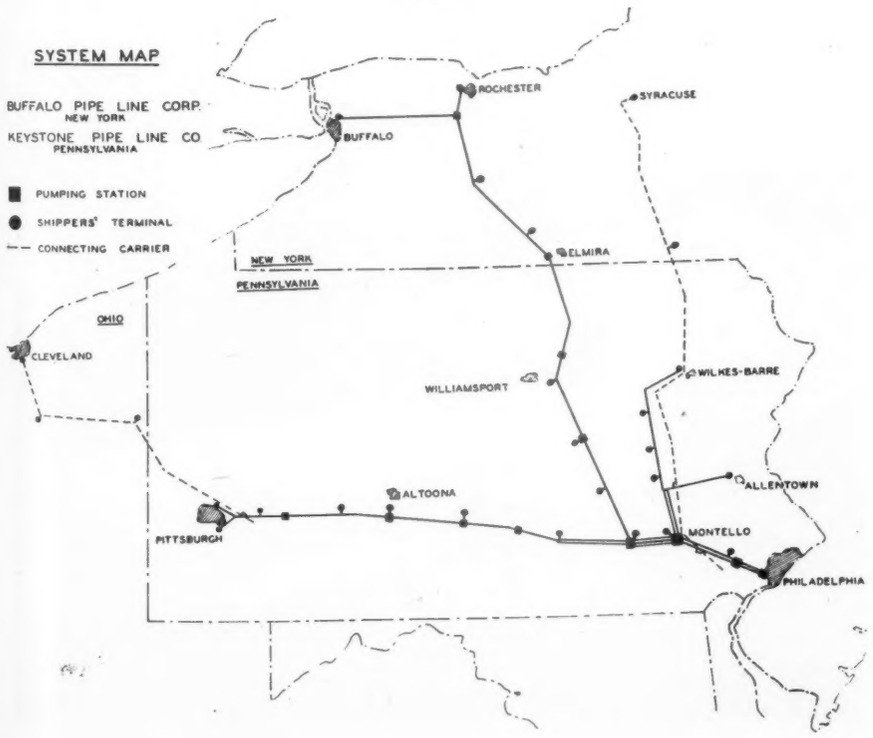
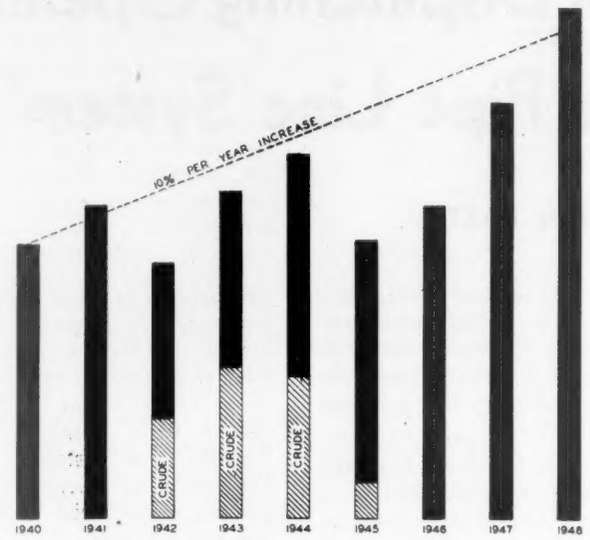


FIG. 2. Barrels transported.



designations, what grade was last received at each terminal to indicate whether a line wash is needed on the next delivery, and any main-line gate valves that might be closed. This proved to be a very reliable system as long as the number of batches in transit at any time remained reasonable, and as long as the velocity of the oil moving through the line allowed sufficient time to make all dispatching arrangements as the batches moved between terminals (Fig. 3).

The increase in transportation demand, coupled with the restriction on terminal tankage, resulted in shorter and shorter replenishment cycles moving at increased velocities through every section of the system. The method of advancing the batches became cumbersome when 25 or 30 batches were a common thing, and the posting of the present position of a batch became inadequate information when the velocity between terminals spaced approximately every 30 miles along the system approached the maximum for each diameter of line.

There was need for a system that would show the relation between the present position of any batch and the forecast schedule for that batch. Dispatching arrangements could then be carried out by simply adjusting the pre-arranged schedule in accordance with the amount that the batch was early or late.

It appeared that this information could best be shown by means of a progress chart upon which the position of each batch would be plotted every hour. This chart is designed with the content of the pipe line plotted as abscissa; and 24 hr, midnight-to-midnight, plotted as ordinate. Along the abscissa, the proper number of gallons from the point of origin, and the locations of terminals, pumping stations, and junction points, are shown and coded. The hours of the day run from top to bottom. The chart is made to a vertical scale of 1 in. equals 4 hr, and to a horizontal scale of 1 in. equals 80,000 gal. The overall dimensions are 22 in. by 65 in. The original is drawn on 4-by-20 profile tracing cloth, and black and white prints of this are then run. One print is used for 24 hours' operation of the entire system. (Fig. 4).

The chart is laid out for the convenience of the dispatcher, dividing the system into three main parts. Horizontally along the top the 8-in. trunk line from Philadelphia to Buffalo is plotted as a continuous graph. Along the bottom of the chart the 12-in. and 8-in. trunk line from Philadelphia to Pittsburgh is plotted. The middle sec-

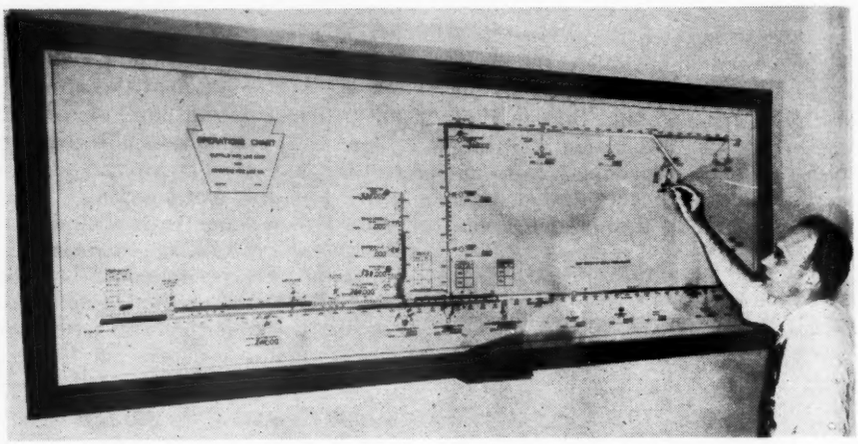
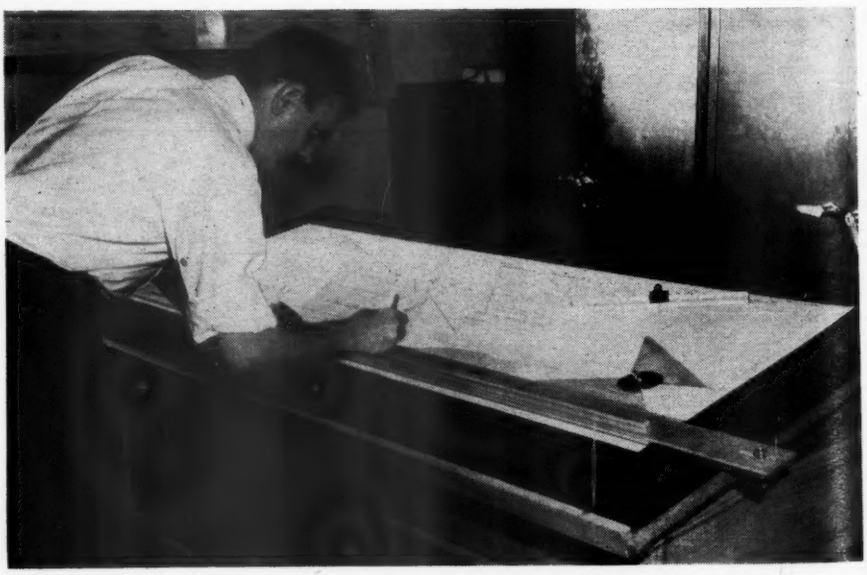


FIG. 3. ↑

FIG. 4. ↓



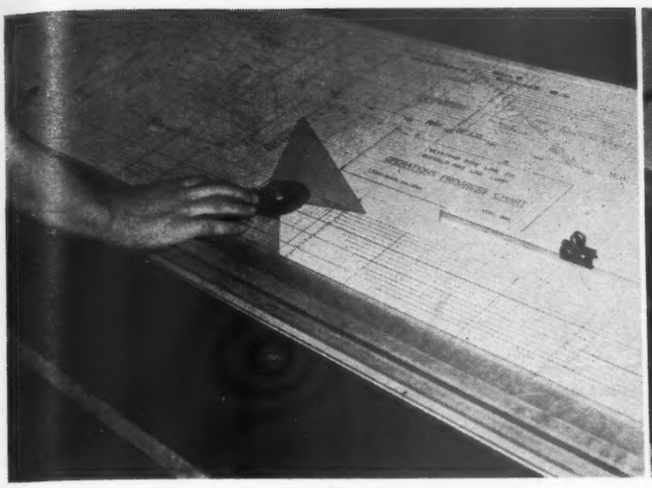


FIG. 5.

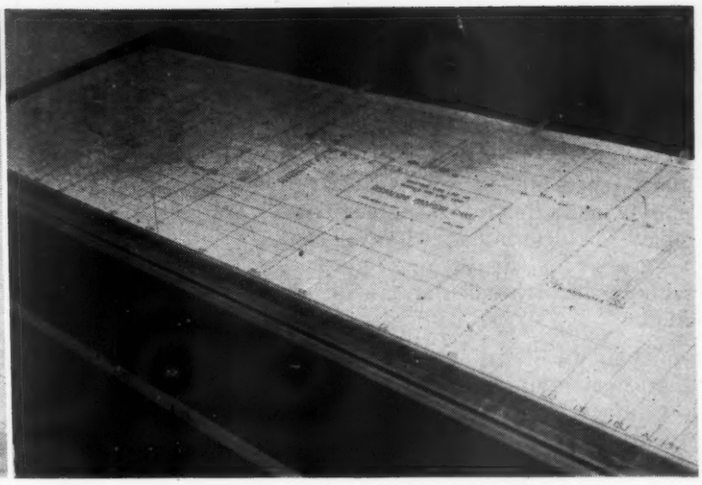


FIG. 6.

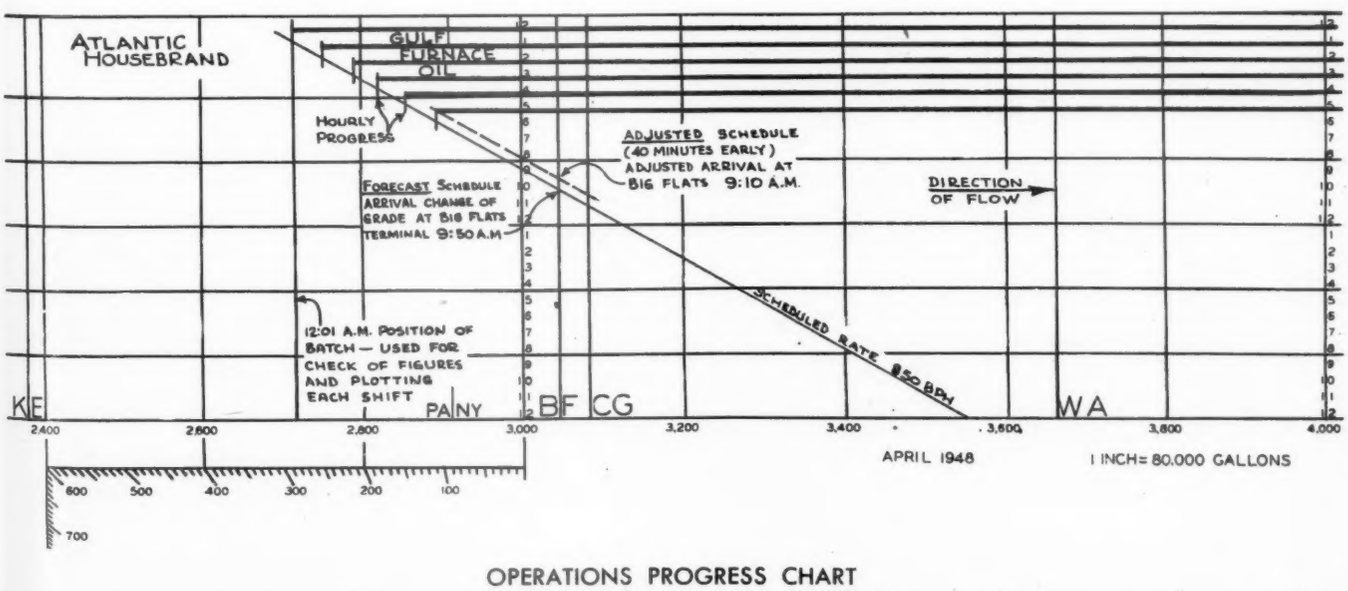
tion is used to show the smaller components of the system, which include a 6-in. line to Kingston, 4-in. spur to Allentown, a 6-in. loop paralleling the 8-in. line from Montello to Mechanicsburg, an 8-in. loop from Montello to Berne Junction with the Susquehanna Pipe Line, and two 8-in. spurs from the main trunk lines, one to Rochester, New York, and the other to Hays, Pennsylvania, in the neighborhood of Pittsburgh. Schedules supplied the dispatcher are divided in this same way; i.e., the Philadelphia to Buffalo system is scheduled as a unit, and the Pennsylvania lines are scheduled separately.

As the chart is a graph of time against volume, a slope on the chart is a measure of the rate of flow; and, to make use of this, the chart contains two conveniently located scales showing the relationship between slope and rate. This, of course, is the heart of the entire scheme (Fig. 5).

To facilitate the plotting of the batch locations, and especially the use of the rate scale, the daily chart is mounted on a sloping-top table that is equipped with a full-length parallel-line rule. A transparent adjustable triangle or protractor is used with the parallel-line rule to carry a desired slope from the rate scale to any location on the sheet.

The daily sheet is prepared during the daylight shift prior to the day for which the sheet will be used. At this time the location where each batch will be at midnight of the current day is determined from the position of the batches on the present day's chart. This point is then plotted at the top of the next day's chart as the scheduled position of the batch at 12:01 A.M. From this point the scheduled progress of the batch is plotted through the entire 24-hr period to be covered by the chart being prepared. The rate at which the batch interface moves is determined from the written forecast schedule supplied to the dispatcher—taking into consideration terminals going on or off the line ahead of the batch being plotted as well as other changes in the pipe line rate. Thus, the prepared chart shows an outline of the following day's operation, as scheduled (Fig. 6).

The intersection of the sloping lines



OPERATIONS PROGRESS CHART

FIG. 7. Chart showing adjustment of schedule for batch running 40 minutes early.

drawn on the sheet in this manner, and the vertical lines printed on the chart at the station and terminal locations, represent the arrival time of a change of grade at any given point on the pipe line. Each horizontal line on the chart represents 12 min; so that, by simply inspecting the chart, the arrival times are determined with sufficient accuracy for dispatching purposes without further calculations of any kind.

When the daily chart is put into service at midnight, the actual location of each batch as determined by hourly deliveries to terminals is copied over from the bottom line of the chart for the previous day. This shows at once the position of the batch with respect to the line representing the schedule. For illustration, if this would show a batch running 40 min ahead of schedule, and if there were no further changes anticipated, then the arrival time for this grade at the next station or terminal would be moved ahead 40 min. If it is desired that the product be brought back on schedule, possibly before its arrival at a junction with a connecting carrier, then it is necessary only to draw a line between the present location of the interface and the point where the schedule is to be resumed—and, by using the adjustable triangle, to carry the slope of this line back to the rate scale to determine how much to adjust pipe-line rate (Fig. 7).

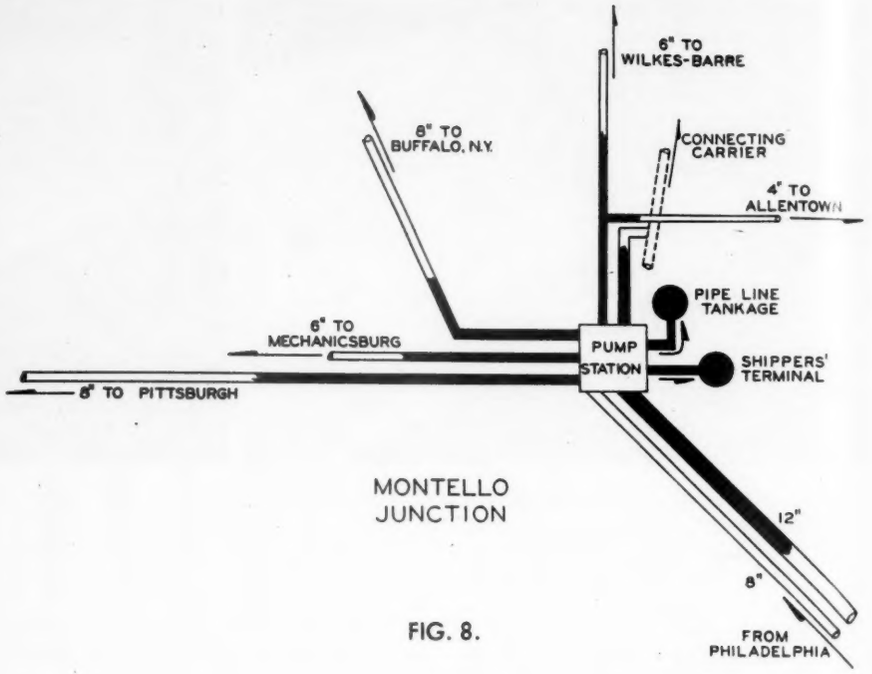
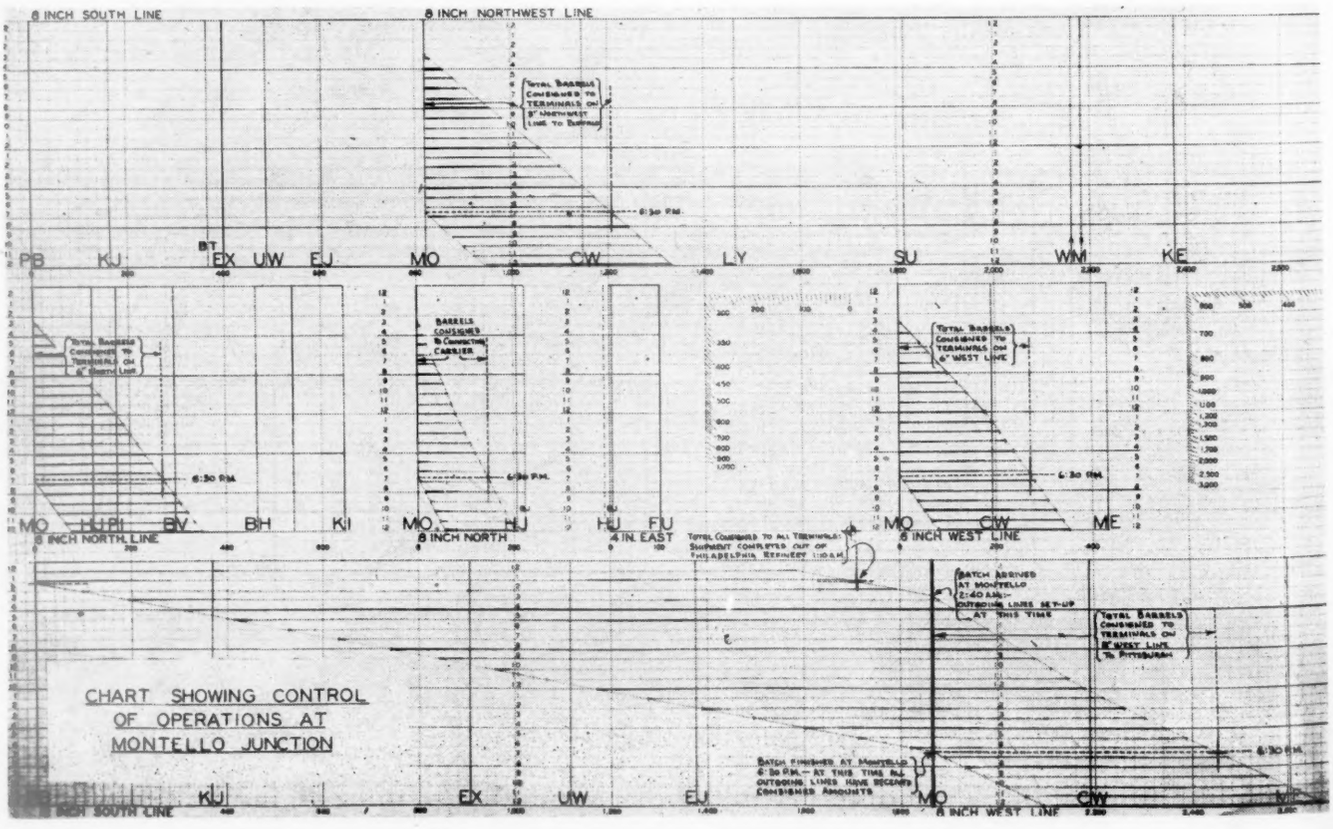
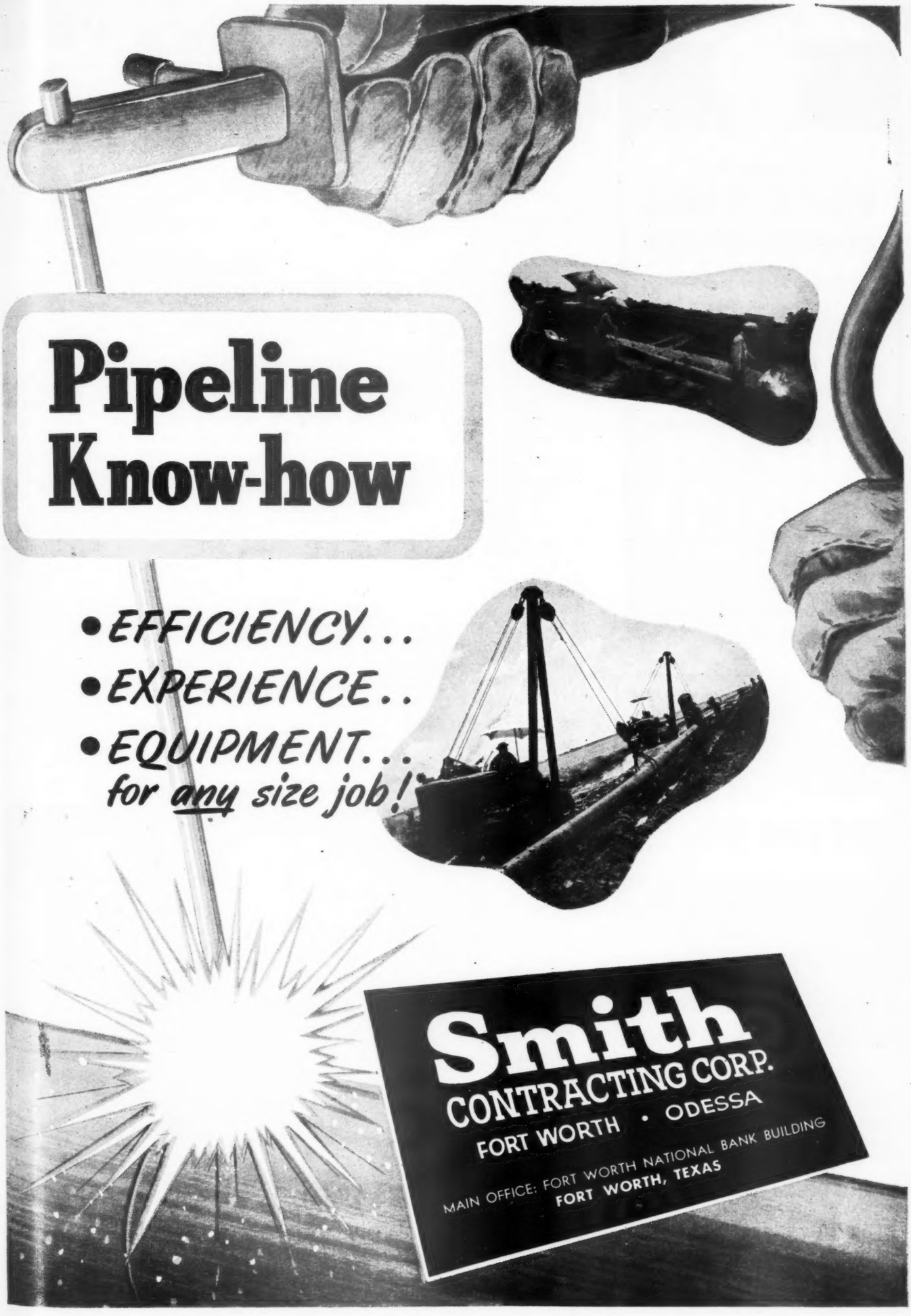


FIG. 8.

Throughout the day the location of the front end of each batch is advanced each hour by the amount of product delivered from the pipe line ahead of each batch. The amount that the batch progressed is obtained from the dispatcher's hourly report from terminals, and a tabulation is kept of the amount used to advance each batch. This tabulation is accumulated at the

FIG. 9.


8 INCH SOUTH LINE
8 INCH NORTHWEST LINE
8 INCH NORTH LINE
8 INCH NORTH
4 IN. EAST
8 INCH WEST LINE
CHART SHOWING CONTROL OF OPERATIONS AT MONTELLO JUNCTION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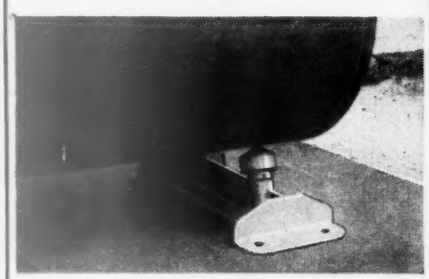
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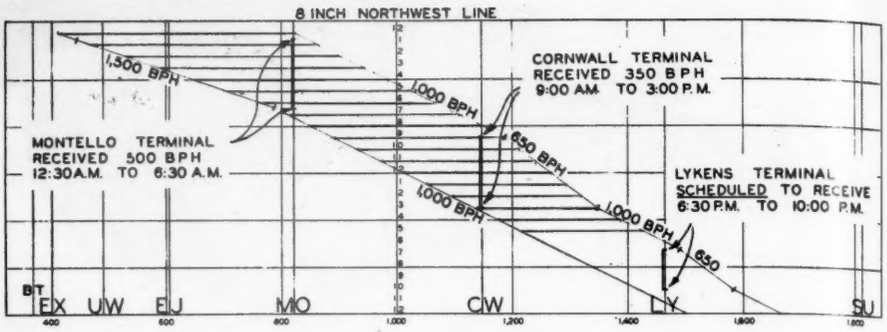


CHART CONFIRMING BATCH LOCATION IN RELATION TO SCHEDULED DELIVERY TO TERMINAL

FIG. 10.

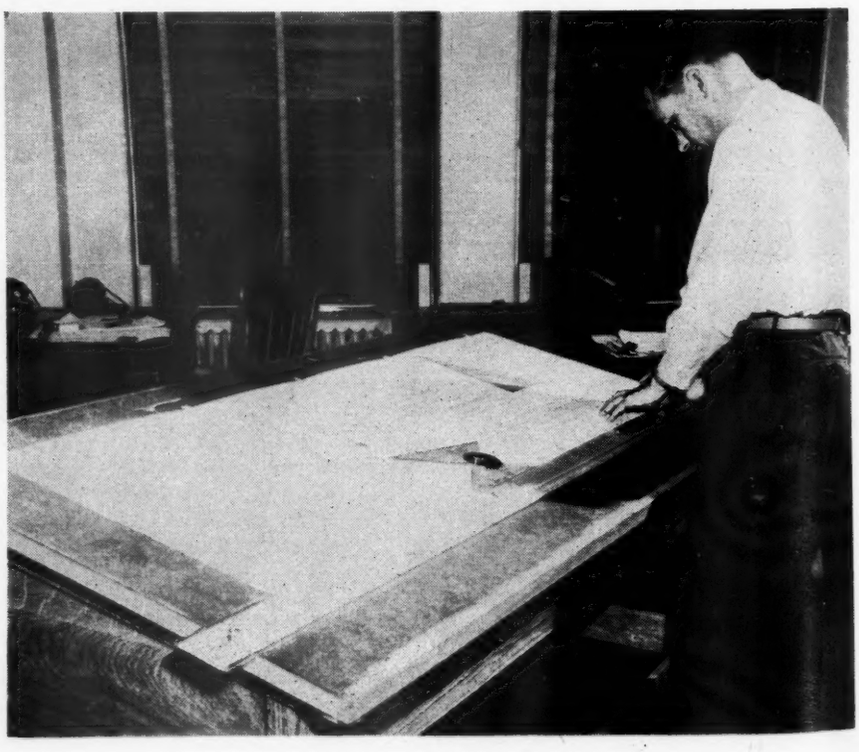
end of each shift and checked against the accumulated deliveries to the appropriate terminals. This serves as a check of the amount used hourly to advance the chart.

After it has been determined from the hourly log how much each batch has moved, this information is plotted on the chart by using a regular engineer's scale divided for 80 parts to the inch. A short vertical line is drawn through the point plotted, and it extends down to the next hourly division of the chart. This line is used for accurately plotting the increment for the following hour. When the current position of the ends of the batches has been determined, the different grades are indicated by ruling an appropriately colored bar to the extent of each batch. Regular colored lead pencils are used for this because they make a uniformly thick line and do not smear. The accuracy of the plotting is checked at the end of each shift by using the accumulated delivery figure to scale from the midnight position to the present position of each batch. Thus, all arithmetic and plotting procedures are checked back to the actual deliveries to terminals.

In addition to the original purpose of indicating the location of the various grades moving through the system, the chart has proved to be useful for many other purposes.

The location of scrapers is visually

FIG. 11.



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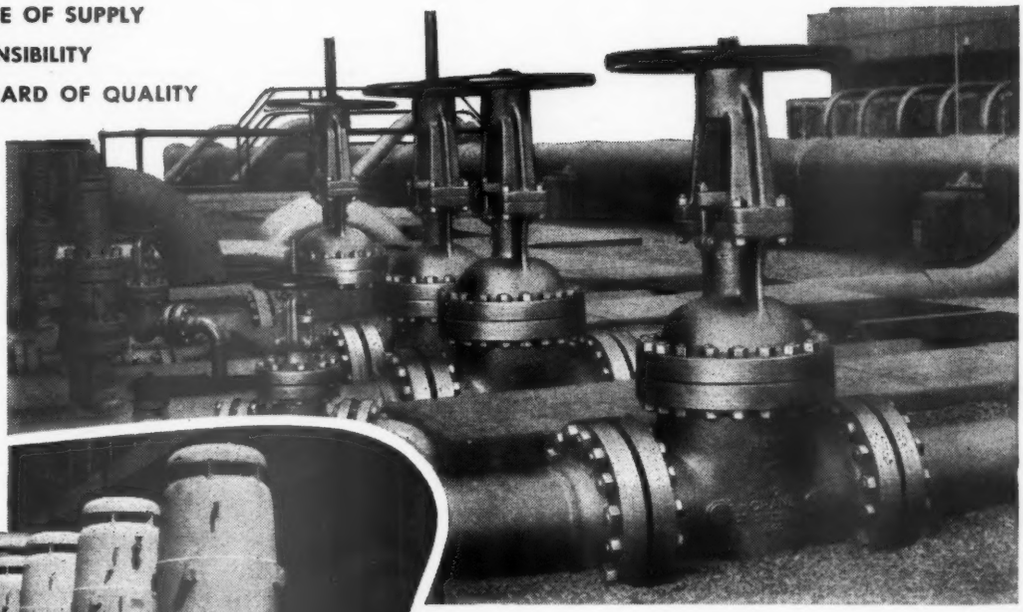

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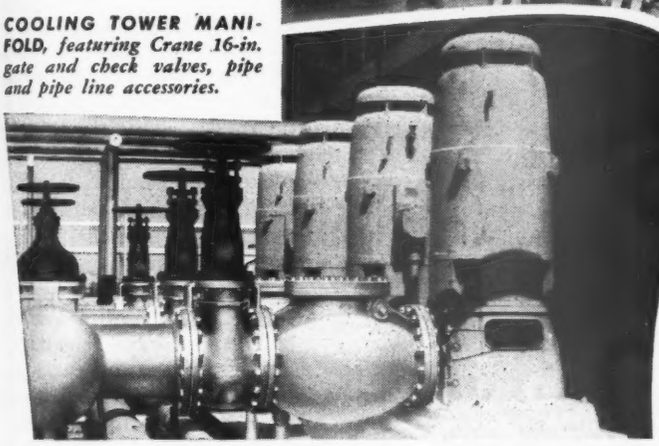
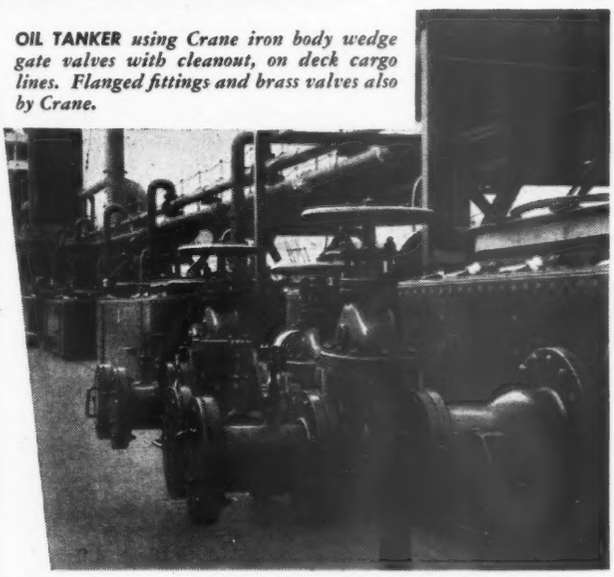


OIL TANKER *using Crane iron body wedge gate valves with cleanout, on deck cargo lines. Flanged fittings and brass valves also by Crane.*



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in One Year

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The mileage of pipeline work done by this one spread was divided as follows:
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Miles of Pipe laid, 8", 10" and 12" . . . 62
Miles of Pipe taken-up and reconditioned . . . 50

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indicated in the proper position in the material in which they are moving.

Emergency shutdowns and power failures do not leave the dispatcher completely without a forecast schedule. As soon as the trouble develops, he can replot the forecast lines on the chart in accordance with the restricted operation, and thus he can determine the effect on the immediate schedule. When the trouble is cleared, he can start from the actual location of the batches and plot a rate to regain the time lost so as to meet the original schedule at a specific time, or he can plot to any objective which the chief dispatcher or forecasters may desire.

The chart is used to control the proration of products passing Montello, which is the main junction point on the Keystone Pipe Line system. This is approximately 60 miles from Philadelphia, where the system branches to Pittsburgh, Mechanicsburg, Buffalo, Kingston, and Allentown. There is an 8-in. and a 12-in. line coming into Montello from Philadelphia; an 8-in. line going west from Montello to Pittsburgh; a 6-in. line going west to Mechanicsburg; an 8-in. line going northwest to Buffalo; a 6-in. line going north to Kingston; and an 8-in. line going north to Berne Junction, where it connects to Susquehanna Pipe Line for movements to Syracuse, and where it also connects to a 4-in. line to Fullerton Terminal, near Allentown. At Montello there is a pumping station, 5 tanks belonging to the pipe line company, and sales terminals for 3 shippers consigning 10 different grades (Fig. 8).

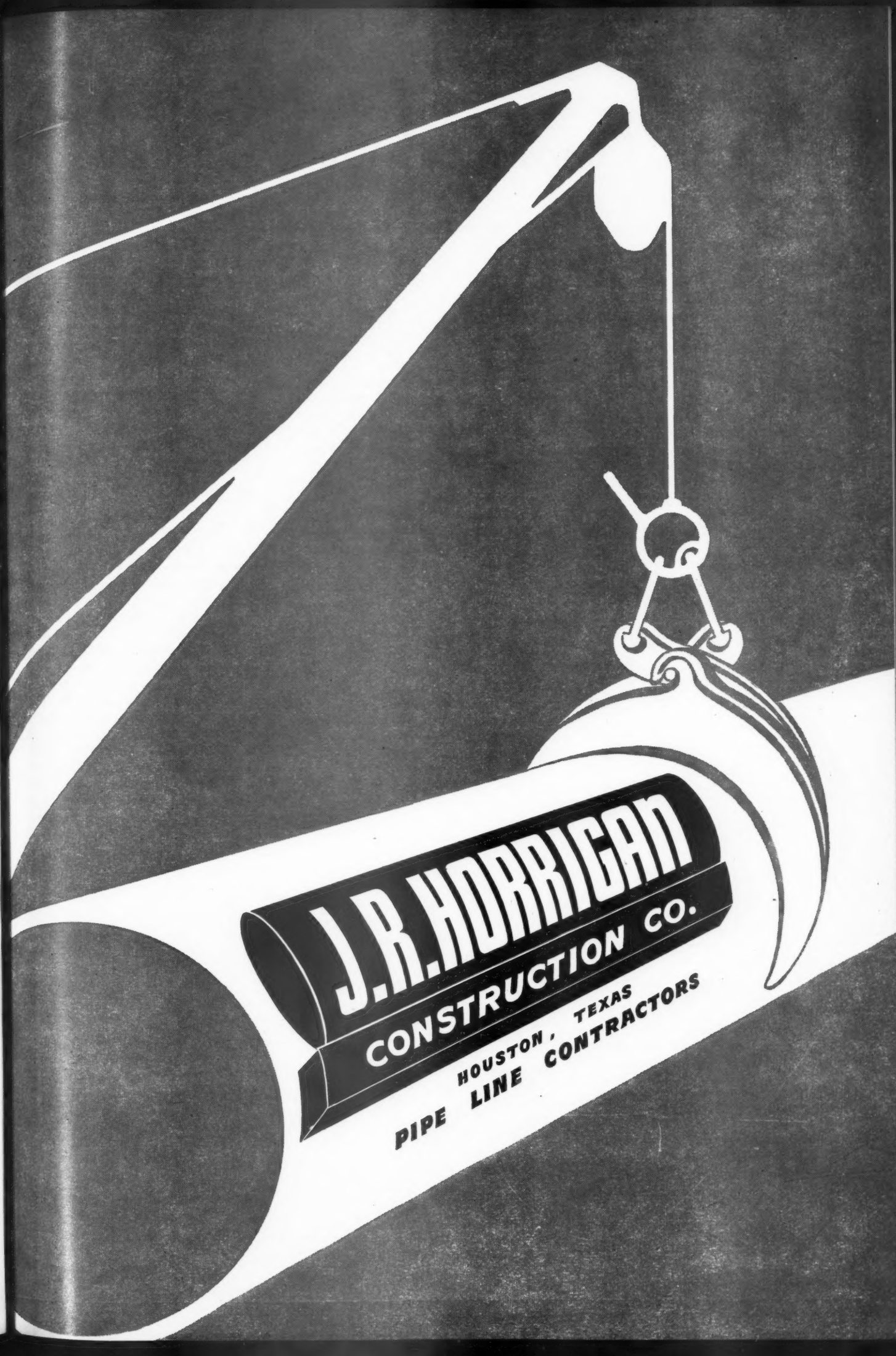
When a product arrives at Montello in one of the lines from Philadelphia, it is directed into the proper outgoing lines according to the shipper's destinations, and also into Montello Terminal and into the pipe line tanks, if so scheduled. During the entire period that this product is passing Montello, the operations of all the lines or terminals involved are so scheduled that exactly the amount consigned will be pumped into the respective lines. This calls for very close coordination of the rates going out on as many as five lines, into two separate tank farms, and the total of all these rates which move up the incoming line. Checking the status of this complicated arrangement was a constant requirement, and a time-consuming one, prior to the use of the graphic method. With this scheme, however, the location of the product moving in each line, and its relation to where it was scheduled to be, is clearly visible on the chart. Any adjustment necessary can be made graphically so as to bring the lines right up to schedule at the time the back end of the batch arrives at Montello (Fig. 9).

If an intermediate terminal near the end of a trunk line is scheduled to receive from a batch that has been greatly reduced by earlier deliveries, and if, therefore, it will be passing this terminal for only a few hours, the chart will show at what time this grade will arrive and finish at this terminal, and the delivery time or rate can be arranged accordingly (Fig. 10).

Following the same line as these few examples, the dispatchers themselves have worked out many other ways in which to take advantage of the graphic method for making the decisions required by the countless details of each day's operations.

When the new system was put into use, the change-over was made abruptly and completely. At 12:01 A.M. the position of the various batches was plotted on the first chart, and the old system was abandoned at once. Instead of a feeling of confusion or uncertainty, which would be expected with any new system, the dispatchers picked up immediately the possibilities of this visual plan. A few hours' instruction as each man came on duty for two or three days was all that was necessary to get the system working. Even the men who had no previous training or experience with graphic representation were completely on their own after two or three shifts, and were suggesting improvements in the technique by the end of a week. The replacement of the static board, which showed the current location of batches with the progress chart which has one dimension in time, had all the advantages that would come from telling a story with motion pictures instead of stills. It was like supplying the dispatchers with a working-scale model of the system, in place of a schematic drawing (Fig. 11).

The effectiveness of the graphic method, which gives the dispatcher better control of the system by giving him a better picture of the status of his operations and a means of promptly detecting and adjusting irregularities, is probably best indicated by the fact that the chief dispatcher and the forecasters now report that calls at home during the night and over week ends have become the exception rather than the rule. This simply means that the operations are carried out more nearly according to a plan, or schedule, that was worked out to give proper consideration to the efficient use of the equipment and facilities required to meet the total transportation demand on the system at any time. ★ ★ ★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Internal Corrosion of Crude-Oil Tanks†

R. A. BRANNON*

Abstract

Sour crude oils, which are those containing hydrogen sulphide and other sulphur compounds, are quite corrosive to the inside of tanks in which they are stored or handled. The area that produces the greatest volume of sour crude oil is West Texas. The API Subcommittee on Internal Corrosion of Crude-Oil Pipe Lines and Tanks is conducting studies to determine the extent to which other areas produce corrosive oils, and the degree of their corrosiveness. Most of the corrosion damage occurs on tank bottoms where salt water settles, and in the vapor spaces where moisture condenses. Reasonably satisfactory protective coatings have been developed for tank bottoms in the form of bituminous coatings, which are usually applied in the molten state. As a replacement for steel bottoms that have failed, new bottoms constructed of concrete are widely used. In the case of vapor-space corrosion, most protective coatings have proved to be of doubtful value, and additional development work needs to be done by manufacturers of coating materials, and the tank owners. Some use is being made of aluminum as a substitute for steel in the construction of tank roofs and roof-supporting structures. Advancing steel prices have encouraged the use of aluminum, and it appears likely that considerably more use will be made of it in the future. Probably the most satisfactory and economical method of preventing this corrosion has been the use of gunite coatings for tanks. These coatings can be successfully applied to tank roofs, shells, and bottoms. Floating roofs are also used to reduce corrosion because they practically eliminate the vapor spaces. It is understood that additional methods of corrosion control, such as modification of tank construction and use of inhibitors or neutralizers, are being developed.

INTERNAL corrosion of crude oil tanks varies widely in degree, depending upon the nature of the oils contained in or handled through them. Crude petroleum oils may be divided, insofar as their corrosiveness is concerned, into two broad groups. These groups are sweet crude oils and sour crude oils.

Sweet crude oils contain no dissolved hydrogen sulphur and relatively small amounts of mercaptans and other sulphur compounds. Corrosion of tanks handling these oils is usually a minor problem, as it is confined principally to the tank bottoms where salt water settles. It is a relatively simple matter to apply protective coatings to the tank bottoms to prevent this corrosion. Fortunately for the pipeline companies, most of the crude oils produced fall into this group.

Sour crude oils contain hydrogen sulphide and sulphur and other sulphur compounds in varying amounts. These oils are corrosive to tanks in varying degree, depending upon the amount of sulphur and sulphur compounds present, as well as such other dissolved or suspended matter such as salt water, iron sulphide, and other substances. It appears that the corrosion rate is affected not only by the presence of the individual corrosive agents, but by the various compounds in which they occur.

The Subcommittee on Internal Corrosion of Crude Oil Pipe Lines and Tanks is at present making a survey of the industry to determine which fields produce corrosive oils and the extent to which they create corrosion problems among the pipe line companies. My own knowledge of this problem is restricted largely to Texas. The subcommittee has received reports that oils produced in the McKamie field and Magnolia field in southern Arkansas contain high concentrations of dissolved hydrogen sulphide, and are quite corrosive. General reports have been received showing that corrosion is rather severe in the case of oils produced in certain western Kansas fields. More complete information is needed regarding these and other areas where internal corrosion of tanks is being experienced.

In Texas large quantities of corrosive crude oil are produced in West Texas. Some of the smaller fields, such as Sugar Land on the Gulf Coast, also produce extremely corrosive oils. It has been found that the corrosiveness of the oils varies widely between different fields in the West Texas area and that there is a wide variation within the individual fields, and even between adjacent wells. It has also been noticed that corrosiveness varies with time, and that this change is apparently due to changes in composition of the oil produced. For instance, when a well begins to produce appreciable quantities of salt water, the corrosion rate of lease tanks is greatly increased.

Tank bottoms are quite seriously corroded due to settling of salt water, and to settling of scale that is pumped into the tanks with the oil or that falls from the roofs of the tanks. The corrosion of tank bottoms and the lower portion of tank shells that are exposed to salt water is probably more general throughout the area than is corrosion of the other portions of tanks. The severity of this corrosion varies widely. There are reports that 500-bbl bolted lease tanks have failed within six months. Service lives range from six months up to several years. The difficulty of determining the average service life of tank bottoms is illustrated by an example where an employe of an oil company gave the information that untreated tank bottoms at a certain battery would last six months; whereas another employe at this same battery gave the estimated life at four years. Because of the wide variation existing at the various tank locations, it is impossible to measure even approximately the average corrosion rate in inches of penetration per year.

The vertical surfaces of tank shells and columns that support roof structures are not seriously corroded, as a rule, in the area where they are used continuously or periodically submerged in oil. Severe corrosion is usually limited to the vapor space in the upper portion of the tank, and in the lower portion where water settles from the oil. Tank roofs are corroded where dissolved hydrogen sulphide evaporates from the oil into the vapor spaces of tanks. Water vapor condenses from the air contained in tanks.

†Presented before Annual Meeting, American Petroleum Institute, Chicago, Illinois, November 8, 1948.

*Humble Pipe Line Company, Houston, Texas.

and is deposited on the metal surfaces in the form of liquid water. Hydrogen sulphide is dissolved in this water, and corrosion of the steel proceeds at a rapid rate. A surprisingly large amount of water is condensed in the vapor spaces of tanks, even in areas where the humidity of the atmosphere is quite low. The water also remains on the roof structures a large proportion of the time, as it appears that the steel must reach high temperatures in order to evaporate the water that has condensed on it. The vapor spaces of tanks are more severely and more generally corroded than other portions. Measures for preventing this corrosion have been less successful than have the measures employed for protection of tank bottoms.

Economics of Corrosion

The cost to the pipe line industry of internal corrosion of crude oil tanks cannot be estimated with accuracy, but there is no doubt that the economic losses are tremendous and that the problem deserves considerable study. Any organized cooperative effort to improve methods of combating this type of corrosion should receive the hearty support and encouragement of API members. It is likely that conditions will become worse instead of better with the passage of time, as increasing age of producing oil fields usually leads to the production of larger quantities of salt water along with the oil. It is also likely that the handling of sour crude oils will be extended to additional trunk line systems that have been in sweet crude oil service exclusively.

The remedial measures that have been employed have been quite varied in their nature, but until recently have been rather uniform in their results in that they fail to provide satisfactory protection to tanks, especially in the vapor spaces. The remedy that one naturally thinks of first is the application of a protective coating. Accordingly, a number of paints and other preparations were tried several years ago—with results that were generally discouraging. Although it was possible to apply coatings to the bottoms of the tanks and thus greatly increase their service lives, it was found that none of the coatings available would remain in good condition in the vapor spaces for a sufficient length of time to add greatly to the service life of the tank roofs and the upper portion of the tank shells.

Upon finding that the protective coatings were of doubtful value, it was logical that attention should be turned to the use of materials other than steel for the construction of tanks. In the case of small tanks up to 1000 bbl in capacity, a reasonably satisfactory substitute was found in the use of wooden tanks. Tanks constructed of wood have been, and are being, widely used in areas where internal corrosion is severe. They have obvious disadvantages even in the smaller sizes, however, and no doubt all users of them would be glad to find a more satisfactory construction material.

Some use has been made of tanks constructed of aluminum; and it appears that this material is suitable for tank construction, especially in the roof and upper portions where there is no danger of contact with salt water. It appears that, in the future, the use of aluminum in tank construction will be limited to roof plates, roof structural supports, and possibly the upper ring of tank shells. With the recent increase in steel prices, the cost of aluminum roof plates and roof structural supporting members compares more favorably with the cost of steel roofs. The cost of aluminum roofs in the case of large tanks is reported to be about 1½ times that of steel. When the savings to be made by eliminating the need for painting the outside of such roofs is considered, they become economically competitive—with only a small increase in life due to superior resistance to internal corrosion. Some proponents of this type of roof believe that the service life will be at least doubled, and may be extended to as much as 40 years.

In the case of tank bottoms, a substitute material in the form of a solid concrete floor has been, and is being, widely used. This consists of a reinforced concrete slab, approximately 6 in. thick, which is poured onto the grade inside the tank shell. It is made oil-tight by increasing the thickness near the shell to approximately 1 ft and by calking a V-shape groove between the edge of the concrete slab and the tank shell by means of oakum or other packing material and coal-tar-base plastic material. These bottoms are mainly used in replacing bottoms that require replacement because of corrosion in existing tanks. Inasmuch as these bottoms cannot be salvaged, they can be economically used only at tank locations which are considered permanent. They are usually installed over the old steel bottom, but may be installed directly on the grade with only sketch plates under the shell to support its weight. The cost of one of these bottoms for a 114-ft diam tank in Texas ranges from $5800 to $6200.

Inside the Tank

The protective materials that have been tried and used for protecting steel surfaces inside of tanks are many and varied. Galvanized steel has been rather widely used in the case of bolted tanks, and it appears that the extra cost of this zinc-coated steel is justified in areas where the corrosion is severe. The extension of service life is still not great enough to be satisfactory to most users of these tanks. Various other metallic coatings have been tried, such as lead applied by dipping, and aluminum, zinc, lead and, possibly, other metals applied by spraying the molten metal onto the steel surfaces by the metalizing process or other methods. There has been little success with these coatings, and their use has been quite limited.

Bituminous coatings have been quite successfully used in coating tank bottoms. These coatings consist of a primer and an application of bituminous material, which is usually melted and spread over the surface by pouring or brushing. In some cases sand or other inert material is incorporated in the bituminous coating to form a mastic, which has greater resistance to moisture absorption and to distortion by physical forces. Asphalt-base bituminous materials are sometimes used. These materials have the disadvantage that they are soluble in oil, and they require that a layer of water be carried in the tank to prevent contact between the oil and asphalt. It is

ANAEROBIC BACTERIAL CORROSION

(Abstract of paper "Environmental pH as a Factor in Control of Anaerobic Bacterial Corrosion," by J. B. Hunter, H. F. McConomy, R. F. Weston, API Chicago, November 8, 1948).

The results of the study indicate that control of alkalinity of the soil adjacent to a pipe line could be used to inhibit anaerobic corrosion. It is shown that a high alkaline environment inactivates, but does not destroy, the sulphate-reducing bacteria, an alkalinity greater than 9.0 to 9.5 pH must be maintained. Such control of the alkalinity of the soil might be accomplished in the field by electrical or chemical means.

difficult to obtain adequate protection to the tank shell with this material at the oil-water line where corrosion is likely to be unusually severe. Other bituminous materials have a coal tar base, and they are less subject to solution in oil. Usually no effort is made to prevent contact of these coatings with the oil, but settling of water naturally present in the oil sometimes provides this separation.

Several coal tar base coatings with special ingredients have been developed by various suppliers of protective coating materials and offered for use on tank surfaces exposed to crude oil vapors. Some of them have been rather widely used on tanks of all sizes. Indications are that these coatings give full protection to tank roofs for periods ranging from a few months to five or six years. There is considerable evidence to indicate that the destruction of the roof metal is retarded even after the coating shows definite signs of failure.

Probably the greatest hindrance to the more widespread use of these materials has been the high cost of preparing the metal surfaces and applying the protective coating. These coatings, in common with all others of which we have knowledge, require that steel surfaces be cleaned by sandblasting or equivalent methods for removal of all scale and foreign material and for providing a roughened surface for better adhesion of the paint films. Before 1940 the complete cost of such coating closely approached the cost of the steel tank roofs themselves.

During the past few years several paints have been developed that exhibit properties indicating they can be successfully used for protecting these steel surfaces. Synthetic plastic coatings that are insoluble in crude petroleum oil and that can be applied with few microscopic pores have been developed. A number of oil companies are now using these coatings as a regular practice on lease tanks in West Texas. Most of these tanks are of the 250-bbl or 500-bbl size. These companies are also participating in a cooperative effort to determine the effectiveness of the various coatings. Annual inspections are made, and representatives of other companies and anyone interested are given an opportunity to observe the coatings. An attempt is made to arrange the production operations in such manner that as many different coatings, which have been subjected to as many different conditions as possible, are available for inspection. These tanks provide the ideal testing ground for various materials and methods of corrosion prevention, because the tanks are small and have relatively short service lives unless protective measures are employed.

The 1948 inspection was conducted September 14-16, and was sponsored by the Midland Section of the National Association of Corrosion Engineers. It was my observation during this inspection that the plastic coatings as supplied by Goodyear, Minnesota Mining and Manufacturing Company, Amercoat Division of American Pipe and Construction Company, Plastic Coating Corporation, Green Contracting and Engineering Company, Inc., and others afford good protection for periods of one to two years. Some evidence of failure, such as the presence of small blisters, is usually present after one year, but usually there is no sign of metal attack under these coatings even at points of failure, and there is no doubt that the service lives of the tanks will be very greatly extended. In some cases the plasticizer incorporated in the paint has been leached out by the hydrocarbon vapors, with the result that the paint film has become brittle and has lost its adhesion to the steel. No doubt further study of this problem by the paint manufacturers will result in improvements of the paints.

One of the coatings inspected consisted of extremely finely divided metallic lead that had been dispersed in a vehicle consisting of a small amount of plastic paint and a thinning agent. This material was applied by spraying to sandblasted surfaces in much the same manner as any quick-drying paint or lacquer marketed by one manufacturer we know of. It appeared to have good resistance to the action of salt water on tank bottoms and to the action of liquid crude oil. In the vapor spaces it showed blisters similar to other paint coatings.

The cost of almost all these paint coatings, including preparation of the metal surface, application of the paint, and the paint materials, is about 30 or 35 cents per sq ft of area covered.

It is especially apparent in coatings such as these, which show signs of failure after relatively short periods of service, that proper cleaning and preparation of the metal surfaces and the use of proper methods of application are the principal factors in determining the performance that can be obtained from a protective coating. It has often been said that coating performance is based 90 per cent upon application and 10 per cent upon materials. It appears that, in this case, both application and material must be almost perfect in order to provide satisfactory service. Much better results can also be obtained when coatings are applied to new steel than when the same coatings are applied to steel that has been exposed to sour crude oil. It appears to be practically impossible completely to remove all the corrosion products or absorbed material in the case of steel that has suffered corrosive attack by these oils.

Guniting

The protective covering that appears to have been most effective in preventing internal corrosion of all portions of tanks of all sizes is one consisting of reinforced portland cement mortar applied by means of cement guns. This application process is referred to as guniting, and the coatings are referred to as gunite. Gunite coatings have been used for many years on the Gulf Coast by refineries and pipe line companies for protecting the inside of tanks and other vessels. The results have been rather uniformly satisfactory. The metal surfaces are cleaned and prepared for application of the gunite coating by sandblasting to remove scale and roughen the metal surface. Reinforcing steel is attached to the roof and shell by tack welding ¼-in. rods on 18-in. to 2-ft centers. A covering of 3-in. by 3-in. 10-gage wire mesh is then attached by means of tie wires to these rods over the entire surface. Rafters and other roof-supporting structural members are wrapped with the wire mesh so that they can be completely covered with gunite. In tanks where welding is not allowed, the reinforcing rods are attached to the roof and shell by means of clips riveted to the steel plates. Similar reinforcing is placed on the bottom of the tank, except that it is not attached to the bottom. During application of the gunite the steel mat, consisting of rods and mesh, is lifted off the bottom so that it is placed in the center of the gunite layer.

Typical specifications for guniting provide that the cement mortar shall consist of a mix of one part portland cement to three parts sand, and that air pressure for guniting shall be 65 psi, minimum. The minimum thickness of gunite usually specified for the shell is 1 in.; that for the roof is 1¼ in., and that for the bottom is 2 in. The gunite is cured by keeping it wet for a minimum of 48 hr and, where necessary, moist steam is used in the tank to maintain temperatures high enough for effective curing during the 48-hr period. In the case of pipe line tanks, the gunite is frequently applied to the roof and about 5 ft down the side of the shell and the members of the roof-supporting structure. When

gunite is applied to the bottom of a tank, it is usually extended up on the shell-and-roof columns a distance of 2 ft or 3 ft. In a few cases the entire shell has been coated.

Typical prices for the application of gunite coatings to tanks in the Gulf Coast area are as follows:

	Cents per sq ft
Roof, rafters, and girders	42
Tank shell and columns	46
Bottom	50

These prices include cleaning of the metal by sandblasting and supplying of all materials. The customer is usually expected to supply water for mixing gunite and for filling the tanks so that barges may be used as supports for performing work on roofs and tank shells. The customer is also expected to supply electricity for lights, because this type of work can usually be performed better at night when temperatures inside the tanks are lower and, therefore, more endurable by the workmen. Additional charges are made if the use of buggies is required for application of the gunite to the upper portions of the tanks. The cost of moving to remote locations is extra. The cost of this coating is relatively high, but it appears to be quite effective in preventing corrosion for long periods of time, even when the corrosive conditions are unusually severe. Until the effectiveness of less expensive coatings is improved, it appears that this coating is the most satisfactory and economical one available.

In some cases special methods of tank construction have been used to reduce the rate of corrosion attack. Perhaps the simplest of these is the installation of a bottom that is sloped toward a sump so that salt water may be collected and drawn off, thus removing the principal corrosive agent. In the case of bolted tanks, a roof is sometimes installed in an inverted position as a tank bottom. One of these tanks was recently inspected in West Texas after one year's service, and it was found to be in perfect condition. This particular tank bottom had a pitch of 1 in. to 1 ft, and had been installed without protective coating other than the aluminum paint applied by the manufacturer. If this type of construction were applied to larger tanks, the pitch would need to be reduced and a protective coating would be needed because the salt water would not drain to the sump so readily.

Floating roofs are widely used for the double purpose of reducing corrosion and reducing evaporation losses. This type of roof practically eliminates the vapor spaces, and thus greatly reduces the corrosion. It is understood that other types of roofs involving methods for elimination of the vapor spaces are under development.

Another method of corrosion control that is under development, but upon which at present little information is available, is the use of neutralizers and inhibitors. It is possible that corrosion inhibitors could be added to the water carried in the bottom of tanks. It is also likely that corrosion inhibitors or materials that would neutralize the corrosive agents could be added to the petroleum vapors to reduce or prevent corrosion in the vapor spaces. It is known that some producing companies are experimenting with the use of oil-soluble inhibitors for the prevention of corrosion of oil-well casing and tubing. These inhibitors can be expected to remain in the oil, and they have a beneficial effect upon the pipe line carrier's facilities with which they come in contact. The present cost of these inhibitors is too great for pipe line use, but it may be that, if they were widely adopted by producers, a beneficial effect would be noted by the pipe line carriers.

* * *

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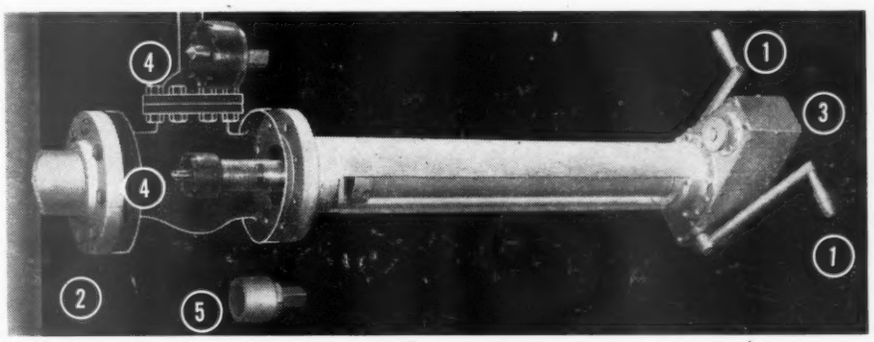

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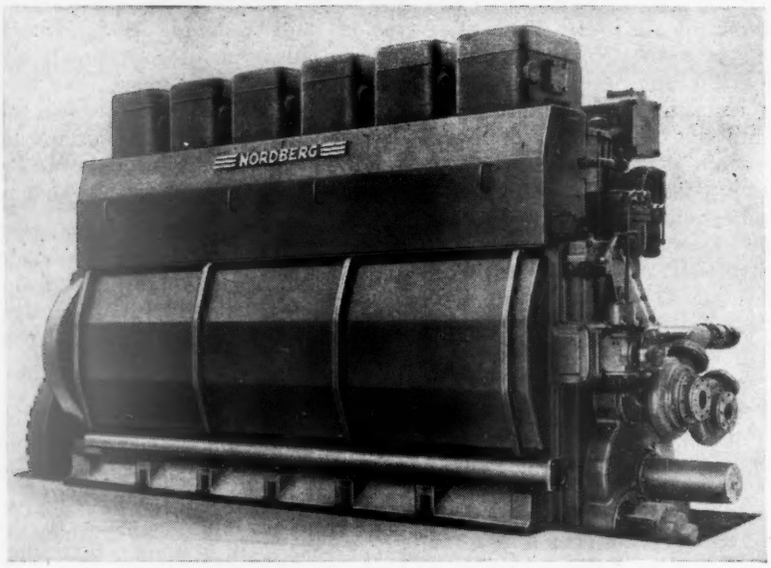

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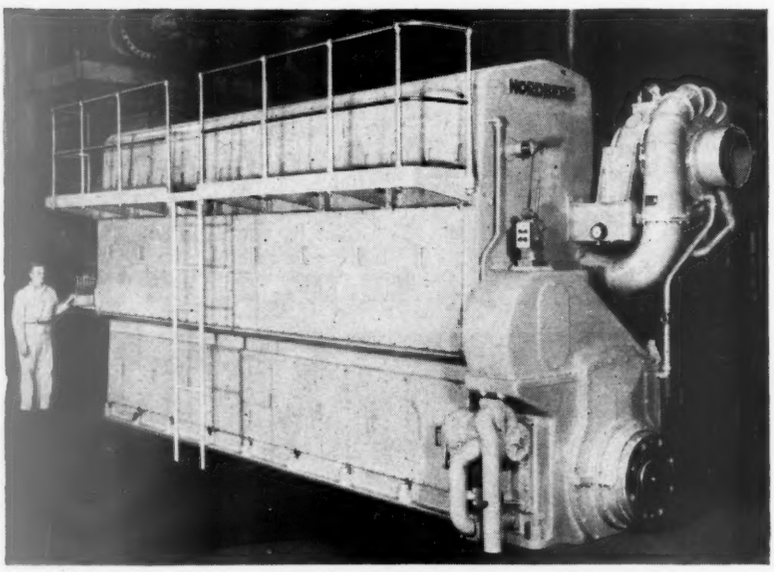

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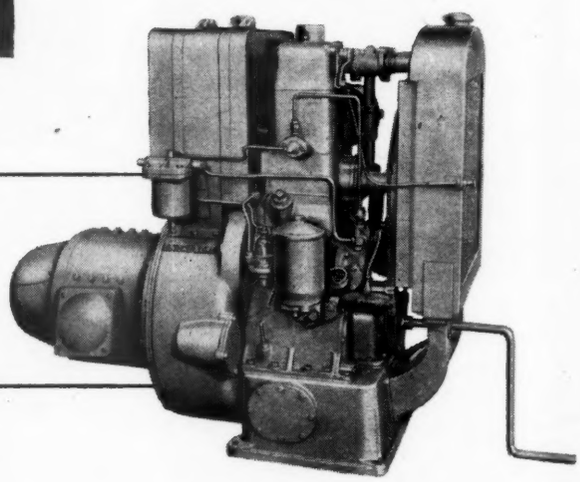

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Mechanical Aspects of Pipe Line Coatings*

L. F. SCHERER† and O. C. MUDD‡

Introduction. To prevent corrosion is the prime reason for coating buried metal structures. All corrosion is electro-chemical action. The soils in which most metal structures are buried contain moisture or water with dissolved natural chemicals. In some locations these have been altered by absorption of fertilizers, industrial wastes, and/or petroleum. Corrosion of metal by contact of soil proceeds only when the latter is moist. Corrosion can be prevented by insulating the metal from the moist soil or by nullifying the latter's electrolytic action.

The corrosion of underground pipe lines has been observed ever since such were first laid, and many and varied steps have been taken to minimize its severity. In recent years industry has generally concluded that coating protection of some form should be provided on new pipe line installations; however, full consideration is seldom given all factors entering into the choice of proper coating materials.

These materials and their application have increased in cost to the point that the latter is a major item in the total cost of a new line. This factor, as well as their relative protective values, requires that every consideration, technical and economic, should be given their specification.

No practical pipe insulating material has been found that will stay completely stable and moisture-proof in the soil over an extended period. The economical alternative is to apply one that will remain reasonably stable under soil pressure and has a low moisture absorption rate, thus retaining an acceptable insulating value, and to compensate for its imperfections by applying cathodic protection. The latter's protective currents decompose any moisture (that may reach the pipe face) into gaseous components, which escape through the coating flaws.

Coating Material Characteristics. No single coating is universally effective, nor is it possible to concisely predict the local actions of the many types of soil conditions that will be encountered along a pipe line. As a practical compromise, it thus becomes necessary to specify a composite coating that will provide the best possible defense under a wide range of conditions.

Certain properties are essential in every good coating. These are:

a. Low moisture absorption.
b. Good electrical insulation.
c. Insolubility in petroleum products.
d. Resistance to soil pressure and deformation.
e. Ease of application.
f. Inertness to soil chemicals.

All economical underground insulating materials have inherent shortcomings, but excellent results—in fact, almost perfect results—can be obtained from a proper combination of materials, and modern methods of application and burial of the coated line.

Early Coating Developments. We will not here discuss all the materials that have been tried to combat underground corrosion because this paper aims to present the best modern practices. However, when considering corrosion preventives, it is just as important to know what won't work as it is to know what will. Thus a brief review of the past seems advisable.

The earliest reports on coating underground pipe came from England in the early 1800's. These showed that hot-applied bitumens gave best results. Later tests have confirmed these findings; thus, recent improvements have been in the selection and mechanical application of such materials.

The American Petroleum Institute initiated a program of coating tests during 1930 that extended over ten years. These tests confirmed the results observed in England many years earlier. One fact brought out was that the true performance of a coating can be determined only after an appreciable time on an appreciable length of operating lines.

Evaluation of Coatings. In the API tests of 1930-1940, and a large number of full-scale tests and observations made concurrently and since under actual operating conditions, different ages and types of coating in service on lines up to 10-in. in diam were studied to determine the better materials and methods of application promising longest coating life with respect to cost. A brief resumé of the coating materials tested and the results obtained are given below:

a. *Asphalt and coal tar in solvents:* These offered little or no protection.

b. *Asphalt emulsions:* These were highly permeable to moisture and under some conditions served to harbor highly corrosive fluids between coating and pipe, thus accelerating corrosion.

c. *Asphalt enamel with cocoa-fiber reinforcing:* Moisture entered through the porous fiber structure, and it was common in later inspection to find an imprint of the reinforcing fabric pattern corroded on the pipe surface.

d. *Petroleum-base or grease-type coatings:* These have very poor electrical insulating properties after a short time in moist soil. Loss of electrical resistance has been found to be an index of their moisture absorption. Moisture accumulates in small globules at the metal surface, thus activating corrosion. Corrosion found under such coatings has been uniformly spread to the extent that when a leak develops it may be impossible to apply a patch and clamps, or even to weld the patch.

e. *Multi-layer coatings where asphalt or coal tar, with organic or semi-organic wrapper, is applied in successive layers:* These proved less effective than a single coat with protective wrapper. The embedded felts contained solvents or moisture, which evaporated into gas or steam when the succeeding coat of hot enamel was applied, thus causing large voids in the coating. These often accumulated water that followed flaws to the pipe surface and caused concentrated corrosion and early leaks.

f. *Asphalt mastic:* Some of these have resisted corrosion for many years in soils free of petroleum or similar solvents. However, crude oil or its products, such as may enter the soil from new or old line leaks, rapidly dissolve these asphalt mastics. In one case on a products line, about 300 ft of coating was destroyed before the leaking product was visible at the ground surface. Also, they are quickly destroyed by marine animals in brack-

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THE AUTHORS

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Mudd assisted in organizing the National Association of Corrosion Engineers, served for a time as secretary-treasurer, and is now treasurer.

ish waters. Because of the permeability of the asphalt, loss of bond between pipe and coating has been observed at many places in wet soils.

g. *Asphalt enamels, with and without wrapper:* Asphalt enamels, even at or near atmospheric temperatures, will flow slowly under pressure. Their tendency to flow decreases with temperature. Asphalt enamels are relatively permeable to moisture; in fact, they often absorb and trap enough water to expand the coating and sever its bond to the pipe. They are soluble in petroleum and similar solvents. Asphalt without wrapper can be severely damaged by soil; also, it tolrates vegetation root growth along the surface and occasionally into it. In some parts of the country this type of coating may be severly damaged by gophers.

Even with cathodic protection, severe corrosion has been found under asphalt enamel with a protective wrapper because the expanded coating had interrupted the flow of protective current and left the pipe surface under conditions equivalent to bare pipe in corrosive soil. The mechanical difficulties encountered in handling a line with this type of protection in warm weather, even though the coating has been well reinforced, make it almost impossible to have a well insulated job without unreasonable cost.

h. *Coal-tar enamel, with and without wrapper:* Coal-tar enamels without wrapper also are subject to severe distortion by soil movement; some fat soils, when shrinking, have frequently pulled the enamel from the pipe surface. The addition of a wrapper of asbestos-felt retards movement or removal of enamel by soil shrinkage and it reduces the deformation of the enamel by soil pressure; however, in some cases the repeated changes of soil dimensions with moisture change have displaced the enamel until the asbestos-felt touched the pipe and provided a moisture path to the metal. No evidence of dimensional change in coal-tar enamels by water absorption alone has been observed.

A four-mile section of a 10-in. crude oil pipe line laid in 1928, coated with coal-tar enamel but without a wrapper, was reconditioned during 1936 because of severe corrosion. This section was recoated with coal-tar enamel, hand-ragged, plus a hand-applied spiral wrapper of asbestos-felt wrapped on cold. All holidays were detected and patched before the wrapper was applied. The section was given cathodic protection, and successive electrical measurements showed no apparent decrease in coating effectiveness.

Two thousand feet of this coating was removed during 1946 to examine the condition after ten years of service. The pipe surface showed no corrosion and no loss of coating bond even though holidays were numerous. Cold flow of the enamel was much in evidence, the areas of greatest thickness having suffered most. Those of approximately $\frac{1}{16}$-in. thickness had been deformed the least and appeared in the best condition. Evidence was found of pipe movement longitudinally within the coating, although this had not severed the bond.

Recent Developments in Coating Techniques. Evidence from these coating studies pointed out the materials giving best results at reasonable cost; however, it also disclosed inherent weaknesses still to be overcome. The evidence showed that a single flood-coat of coal-tar enamel, machine-applied, when supplemented with cathodic protection, gave best results with respect to cost. It also showed that much coating damage is caused by poor trench preparation before lowering pipe and by carelessness in lowering and backfilling.

The improvements indicated by the evidence, and since developed, include the following:

a. The addition of suitable reinforcing material to impede cold flow.

b. The detection and patching of all holidays before pipe is lowered into trench.

c. The thorough preparation of trench (1) by removal of all materials, debris or objects liable to cause excessive pressure against the coating, and (2) by laying along the trench bottom sufficient fine-textured soil or sand to give uniform weight distribution after the pipe is lowered.

d. The exercising of care when lowering in the coated line.

e. The lowering in of the coated line direct from the coating machine when possible, thus avoiding damage from trench skids.

f. The use of a fine soil, free of hard objects, for the first part of the backfill.

g. The exercise of care to prevent debris from falling or being thrown into the open trench or backfill at any time.

h. The application of cathodic protection as soon as possible after line is backfilled in place.

Coating Reinforcement. A suitable reinforcing material to retard cold flow in bitumen coatings must be non-hydgroscopic; i.e., it must not absorb or conduct moisture. Mastic-type coatings contain a high proportion of sand and similar materials for reinforcing, and its application involves the use of considerable material and expensive equipment of great weight.

The practical alternative is to follow the principle of reinforcing concrete with steel; i.e., to place material of high tensile strength in the coal-tar enamel where greatest stresses occur. Glass fiber matting is the most practical material now available at reasonable cost. A mat of 15-mil (0.015 in.) thickness has given best results for

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coatings on pipe 12 in. or less in diam. It should be wrapped into the hot enamel because, if hot enamel is applied over a wrap of dry matting, many air voids and holidays occur. The best results are obtained when the mat is completely embedded in the hot enamel as near the outside surface as practical, and asbestos-felt is wrapped immediately over this coating.

Coatings capable of withstanding severe abrasion and shock can be obtained by mounting short sections or joints on dollies, rotating them, and applying three successive layers of hot enamel with 15-mil glass fiber mat pulled in. If such pipe is to be pushed into position through casings, under highways or railroads, or across streams, it is advantageous to build up "abrasion pads" every few feet over the described triple-layer coating. These pads should be of single mat width and several layers thick, saturated with hot enamel while rotating the pipe. The pads act to absorb abrasion or displace sharp objects during the pushing operation, and they may even help "dig trench" in a pipe pushed or pulled across streams.

Holiday detection and patching of all coating holidays are as essential as testing the line for weld or metal imperfections. Continuity of metal keeps the oil in the line; continuity of coating keeps the metal in place.

Proper preparation of the trench before lowering the coated line is a conservation measure. Excellent coating jobs have been obtained only to be severely damaged when lowered into the trench, and further damaged during backfill. Since bitumen coatings, even with reinforcement, are subject to cold-flow deformation when the pressure is great enough, it is obvious that pressure against the coated surface should be distributed as evenly as practical.

This feature becomes of increasing importance in rock trenches or hard soil, or with larger diam lines where the unit loading is relatively higher. A novel method for handling this situation was used on a recently constructed large-diam line. Fine materials for cushioning were scarce so such material as was available was placed in piles about 6-in. high and at intervals of approximately 50 ft in the bottom of the trench. Several pounds of hot tar from a small patching pot were poured on the top of each pile before the pipe was lowered in. This method proved most effective.

Too often broken pieces of skids, weld rods, and coating barrel fragments have been thrown or have fallen into the trench after the initial backfill of fine soil was laid. Settlement of soil over a long period of time has brought these objects into contact with the coating and has caused holidays.

Much damage has been done to coatings during the lowering-in operation by allowing the line to swing against or drag on sharp projections along the trench walls. Large sheets of plywood placed along these walls during lowering will minimize such damage. These sheets should be held in place until the line is secure against further movement, after which they can be transferred ahead.

With proper reinforcing and reasonably careful handling, it is now entirely practical to lower a coated line directly into the trench behind the coating machine, thus saving considerable expense in further handling of the line and in repair to skid marks.

Frequently too little attention is given to the backfill operation, and large clods or rocks often are pushed in with the first part of the backfill. Too much stress cannot be placed on the damage that may result to the coating from inattention to this feature.

As a good practice in handling "slack loops," the trench should have objectionable material removed before picking up the loop. After picking up, repair the skid marks and then holiday detect the exposed coating to verify its continuity. Then lower in the line and backfill with care equal to that given the remainder of the line.

Application of cathodic protection to coated pipe as soon as possible after it is laid will effect the least consumption of electrical energy for complete protection and will insure against any start of corrosion where undetected holidays remain.

Coating Larger Diameter Lines. Present trends are toward construction of larger diameter oil lines and, as mentioned previously, their coatings are subjected to greater pressure along the underside supporting area.

A 20-in.-22-in. line recently laid from Jal, New Mexico, to Wichita Falls, Texas, via Midland, was coated with coal-tar enamel, glass-fiber reinforcing, and asbestos-felt wrapper. It was deemed advisable to use 25-mil glass-fiber reinforcing in this coating for added insurance against cold flow under the weight of this large pipe when filled with oil. It was not considered practical to embed this 25-mil glass into a single flood-coat; therefore, a double-coat, double-wrap traveling machine applied an initial flood-coat, followed by the reinforcing of glass fiber, and a second flood-coat followed by a wrapper of 15-lb asbestos-felt. The average thickness of the complete coating was less than ¼-in.

A scrupulous inspection for holidays was maintained immediately behind the coating machine; holidays were patched as rapidly as they were detected. A 4-mile section of line was checked for coating resistance a few days after backfilling. It measured more than 24 megohms per sq ft, which resistance undoubtedly decreased after complete settlement of the backfill. Nevertheless, that measurement indicated that a good job had been done.

A commercial form of casing spacers, designed to hold the pipe centered in the casing, was installed over the sections of coated pipe that were pushed through casings at road crossings, etc. These spacers were constructed of synthetic blocks, suitably shaped and arranged on flexible metallic cable, with provision to maintain equality of spacing and tight attachment around the coated pipe.

These assemblies, which were fastened around the pipe at 15-ft intervals, proved very effective in centering the pipe within the casing so that much less effort was required for the pull. They also eliminated the likelihood of wood or other fibrous materials, loose wires, etc., being left within the casing.

A commercial form of mechanical end-seals for the casings was installed, which gave better insurance against incidental pipe-to-casing contacts than other types previously available.

Preparation of Pipe for Coating. It is important that pipe to be coated should be as clean as possible so that it will bond properly with the coating. New pipe can usually be prepared for coating primer and the succeeding hot enamel application without much trouble; however, proper cleaning of old pipe removed from the ground presents many problems.

Numerous pipe-surface cleaning methods are in use, but the rotary-head traveling cleaning machines are still the favorites. With these it has been found that better cleaning of rough pipe is possible if one cutter-head rotates in a clockwise direction and a second cutter-head rotates counterwise. Such an arrangement seems best adapted for cleaning out deep pits or along rough edged longitudinal welds on certain types of pipe.

In preparing pipe surface for coating, it is important to remove loose soil and corrosion products or scale, but it is even more important to remove all moisture from adhering substances. Cleaning of the base metal accomplishes this, but the removal of moisture by chemical methods is cheaper. Rough corroded surfaces reasonably cleaned and chemically

treated have provided excellent bond for hot enamel coatings. In one method of cleaning now in vogue, a rotary-head cleaning machine is run to remove dirt and scale prior to inspection for corrosion damage and subsequent repair. After the repair work, a second machine, with cleaning head to remove additional loose scale, and with brushes to apply a solution of dilute primer (diluted with four parts of thinner) to soak any remaining rust or scale, is run. This does not remove all of the moisture, but the amount left will not cause trouble. Its effectiveness is often shown by the appearance of chemicals over the treated surface after the primer dries. A third machine is then run over the treated surface. This machine is fitted with a cleaning head to remove any scale loosened by the dehydrating action of the dilute primer and with brushes to apply the regular or full-strength primer.

Other methods of cleaning may be justified by circumstances. On some older lines uncovered for reconditioning, corrosion products have been found that gave trouble even after treatment with primer solution. In some such exceptional cases the trouble was eliminated only by "grit blasting."

Checking Coatings in Place Underground. Two methods are now popular to verify effectiveness of coating underground.

An electrical resistance test can be made only when the coated pipe is electrically isolated from other structures intimately in contact with ground. When thus isolated, an electrical current of negative polarity is impressed upon the pipe until the most remote point is slightly over 0.25 volt negative to soil (0.80 volt with copper-sulphate electrode); then the current flow and potentials at control points are noted. Additional current is then impressed to raise the remote point of pipe-to-soil potential by 0.1 volt, i.e., to 0.35 volt, after which the current and potentials are again noted. If the test is conducted with the current connection at one end, then the average potential for any current value will be the sum of the potentials at each end divided by two. Dividing the difference of the two average potentials by the difference of the two current values will give the total resistance for the line coating. Dividing the total resistance by the total square feet of pipe surface under test will give the resistance per square foot. If—after the backfill has settled—the unit resistance is less than one megohm per square foot, the effectiveness of the coating is questionable.

The other method of coating in the ground is by the use of the Pearson Holiday Detector, which locates the coating flaws by detecting the points of current flow from the soil into the pipe. This instrument is dependable in experienced hands, and it has revealed many such flaws. When used to inspect newly laid lines, it has multiplied the bane of contractors—"Hard Boiled Inspectors."

Experience has developed coating specifications for new construction or maintenance jobs with provisions aimed to obtain best results. However, these are without force unless constant vigilance is maintained by inspectors qualified to judge the character of the work and authorized to enforce compliance.

Coating specifications doubtlessly will change as improvements develop; however, the following current specimen has evolved from experience.

Specimen Specifications for Application of Coating and Wrapping (Herein Called "Protective Coating") on Pipe Line

a. *General:*

1. These specifications are intended to cover the complete application of the "protective coating," and neither anything herein contained nor the omission of any essential provisions herefrom shall be construed to relieve CONTRACTOR of any duty or obligation necessary for the complete application of said "protective coating."

2. All work to be done hereunder by CONTRACTOR shall be conducted diligently, continuously, and in good faith, in a thorough, careful, skillful and workmanlike manner, in full accordance with good pipe line construction practices, and to the complete satisfaction of COMPANY inspectors.

3. All pipe shall be cleaned, primed, enameled, and wrapped in the field, using traveling type machines properly designed for the work to be done and approved by the COMPANY. CONTRACTOR shall furnish all equipment, labor and supervision, and all other expense, including royalties for equipment used for cleaning, priming, enameling and wrapping of all pipe, vent pipes, valves, fittings and connections in accordance with specifications.

4. The work shall consist of machine and hand cleaning the pipe, priming the pipe with coal tar primer, application of a $\frac{3}{32}$-in. average coating of coal tar enamel, application of a glass fiber reinforcing and/or a 15-lb coal tar impregnated felt wraper, electrical inspection for presence of holidays and repair of holidays, using the aforementioned coal tar coating and wrapping materials.

5. The general specifications of the materials being supplied by the COMPANY are as follows:

(a) Enamel:
(b) Primer:
(c) Reinforcing:
(d) Shield:

b. *Handling Coating Materials and Coated Pipe:*

1. Coating materials consigned to the job shall be properly stored to prevent theft, damage, or deterioration.

2. Primer paint shall be kept in CONTRACTOR's warehouse, and only the daily requirements may be strung on the right of way. Drums are to be kept closed to prevent entrance of rain water, dirt, or loss of solvent.

3. Asbestos felt and glass fiber wrapper shall not be strung along the right-of-way, but shall be transported along the line in a covered conveyance and removed as needed, directly from the conveyance to the wrapping machine.

4. The coating and wrapping materials shall be hauled in such manner as to prevent injury to packages. No packages shall be dropped or thrown from trucks, and packages shall not be handled with hooks. All rolls of glass fiber reinforcing and/or felt wrapper shall be stored on end in a dry place, kept from contact with concrete flooring and protected from the weather. Any such materials, which in the opinion of COMPANY'S inspector show evidence of deterioration while in CONTRACTOR'S custody due to weathering or any other cause, whether similar or dissimilar, may be rejected by COMPANY and the cost of same deducted from final payment to CONTRACTOR.

5. Coated pipe shall be handled at all times with wide non-abrasive canvas or leather belts, or other equipment designed to prevent damage to the coating. All such equipment shall be kept in repair so as to prevent injury to the coating. The use of tongs, bare pinchbars, chain slings, rope slings without canvas covers, canvas or composition belt slings with protruding rivets, pipe hooks without proper padding, or any other handling equipment found to be injurious to the coating shall not be permitted. All skids used to support coated pipe shall be padded. Walking on the pipe shall not be permitted.

c. *Cleaning and Priming:*

1. In preparation for the application of primer, pipe shall be cleaned until free from all loose mill scale, rust, scale corrosion products, pipe coating, dirt, grease, moisture, or other foreign material. Grease or heavy oil shall be removed with a

volatile solvent. Loose rust, mill scale, dirt, etc., shall be removed to satisfaction of COMPANY inspector by mechanical cleaning machine using impact wheels and/or knives and wire brushing sufficiently to remove all materials other than tightly adhering mill scale or primer. All "used" or "second-hand" pipe shall be cleaned first by one pass of the mechanical cleaning machine and coated with thinned primer (a solution of one part coal tar pipe line primer with between three to five parts—as stated in the purchase order—thinner added), and then cleaned with a second operation of the mechanical cleaning machine and primed with a regular coat of coal tar pipe line primer. All "new" pipe shall be cleaned with a minimum of one operation of the mechanical cleaning machine and primed with a regular coat of coal tar pipe line primer.

2. Cleaning and priming operations shall be performed over the ditch before application of enamel and wrapper, which are to be applied also over the ditch. The thinned and regular primers shall be applied by mechanical brushing machine (immediately after the cleaning operations) in a thin, uniform coating, leaving no drops or runs, and covering the entire surface of the pipe. Any holidays or unprimed places revealed by inspection shall be reprimed immediately: any flooded areas or primer applied on improperly cleaned pipe shall be cut down to the surface of the pipe and reprimed. Application of primer during a rain or when pipe is wet shall not be permitted. Sufficient time shall be allowed for primer to dry before second cleaning and priming operation or application of enamel. Primer shall be kept in closed containers when not in use to prevent entrance of dirt or rain water, or loss of solvent. Coal tar primer thinner is to be used for thinning coal tar pipe line primer.

3. Freshly primed pipe shall be supported so that it will not come in contact with dirt and weeds; and traffic that raises excessive dust along the windward side of the primed pipe shall be prohibited. Any pipe allowed to stand overnight or to become wet after cleaning and before priming shall be recleaned before priming. All pipe that has accumulated an excessive coat of dust before the primer is dry or that has been exposed to the weather for more than 48 hr after priming or become "dead" in the opinion of COMPANY'S inspector, shall be reprimed before application of the enamel.

b. *Melting the Enamel:*

1. Coal tar pipe line enamel shall be cut up on a platform or other place free from dirt, weeds, or other forms of contamination and hauled to the heating pots in clean truck beds. The broken enamel shall be placed in a clean metal melting pot and heated on reduced fire to the application temperature without reaching a temperature at any point in the pot in excess of manufacturer's recommendations. Melted enamel shall be stirred continuously or at least once each 15 minutes during the heating period with metal agitators (wooden paddles or sticks shall not be used). Mechanical agitated thermostat controlled heating pots are to be used if available to CONTRACTOR.

2. All melting pots shall be cleaned whenever coke or other deposits form on the heating surfaces. If melting pot equipped for continuous operation is used, constant stirring is necessary to prevent local overheating. All enamel heating kettles shall be equipped with thermometers of range suitable for the temperatures to be encountered, and the melted enamel shall be maintained at temperatures as specified during application. Any enamel that has been heated in the kettles to a temperature in excess of manufacturer's recommendations shall be condemned and dumped, and all enamel so condemned shall be chargeable to the CONTRACTOR.

3. Enamel drawn from the kettles shall be strained through a 1/16-in. mesh strainer, so located that it can be readily cleaned.

e. *Application of the Enamel:*

The enamel shall be applied by the machine method to the clean dry surface of the primed pipe at a temperature which, in the opinion of COMPANY'S inspector, produces best results and not below the minimum temperature at which the enamel will fuse with the primer on all sides of the pipe to form a coating that cannot be peeled from the pipe. (Minimum application temperatures depend upon atmospheric temperatures, weight of the pipe, and conditions of application.) The enamel shall be applied in one or more coats in such a manner that a continuous tightly adhering film of enamel with an average thickness of 3/32-in. shall cover the entire surface of the pipe. Thickness and uniformity of the film shall be determined by means of visual inspection. All coating shall be subjected to electrical holiday detector test for continuity.

f. *Application of the Wrapper or Wrappers:* (Cross out one not applying under contract.)

1. *Single coat and wrap:* Immediately following the application of the enamel and before the enamel is cold, the glass fiber reinforcing shall be applied over the enamel in a uniform spiral wrap with a spiral wrapping machine in such a manner that the glass fiber reinforcing will be drawn into the hot enamel, causing enough enamel to penetrate through the glass to furnish a layer of enamel over which a 15 lb coal tar impregnated pipe line felt wrapper shall be applied spirally by the same machine in such a manner that the latter wrapper is in contact with the entire outside surface of the enamel.

2. *Double coat-double wrap:* Immediately following the application of the enamel and before the enamel is cold, the glass fiber reinforcing shall be applied over the enamel in a uniform spiral wrap with a spiral wrapping machine in such a manner that the glass fiber reinforcing will be drawn into the hot enamel. This will be followed immediately with a second coat of hot enamel, followed by a spiral wrap of 15-lb coal tar impregnated pipe line felt wrapper applied with the same machine over the enamel in such a manner that the wrapper is in contact with the entire outer surface of the enamel.

3. The overlap at the edges of the wrappers shall not be less than ½ in. and not more than 1 in. No wrinkling in the wrappers shall be allowed, and all end laps shall be cemented down with hot enamel to secure a firm wrapping. All torn, abraded, or mutilated spots in the pipe coating shall be repaired, to the satisfaction of COMPANY'S inspector and in accordance with the above specifications. All coating operations shall be subject to the aproval of COMPANY inspector, who shall cut samples from the coating from time to time for determination of thickness and bond of coating. After the coating and wrappers have been applied, a test with an electric holiday detector will be made, and all coating defects, damaged areas, and holes (necessary for the inspection of the coating) shall be patched by the CONTRACTOR or as directed by COMPANY'S inspector.

g. *Application of Multi-Layer Reinforced Coating:*

1. All pipe to be placed inside of casings, across streams and swamps or other locations where the coated pipe is to be pulled or pushed into position, shall have three coats of enamel and three wraps of glass fiber reinforcing (enamel and wrapper to be applied in alternating layers) applied to individual joints of pipe before welding or making up into a continuous section as indicated in detail in Exhibit —— and/or described herein.

2. Multi-layer reinforced coating shall be applied by rotating the pipe and applying three alternate coats of enamel, 2/32-in. average thickness, and three spiral wraps of glass fiber reinforcing, each completely submer-

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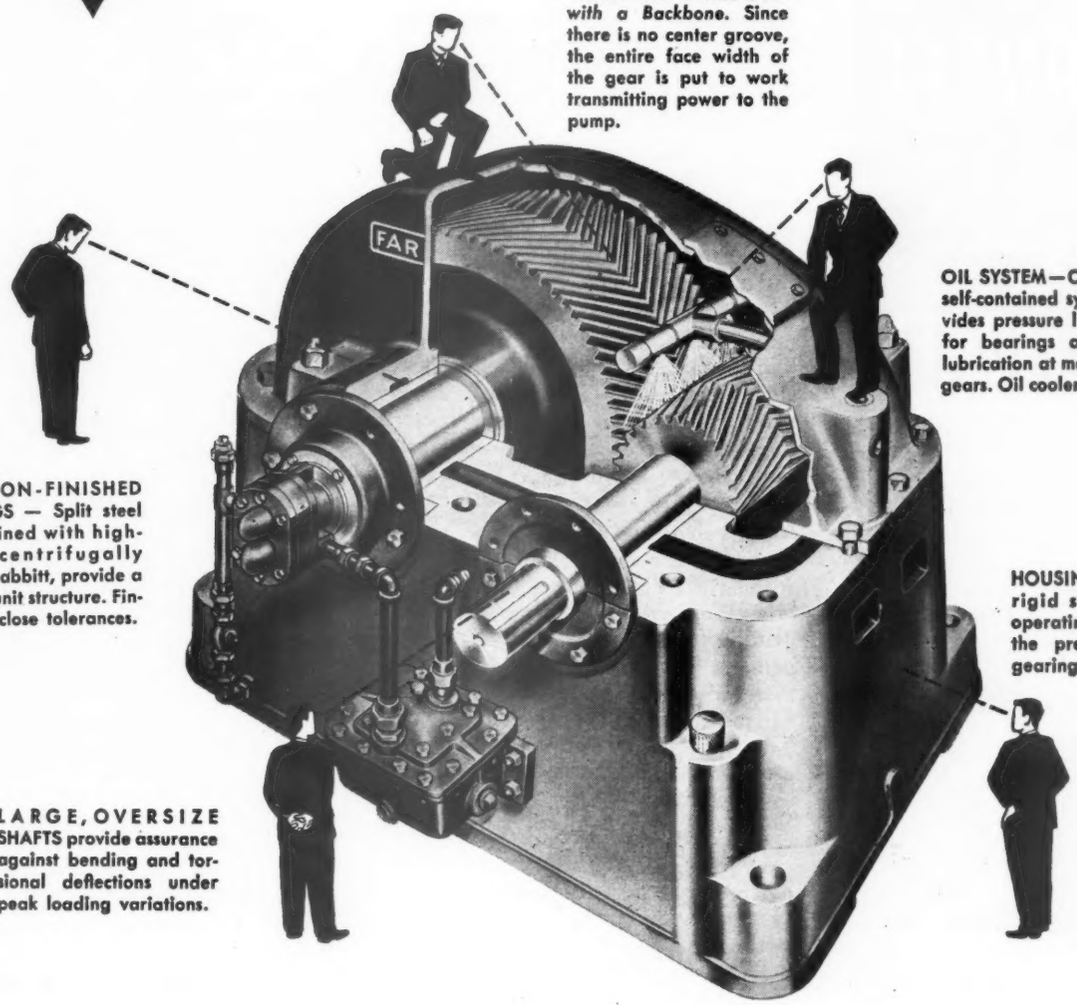

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ged in the preceding coat of hot enamel. Rotation of the pipe may be accomplished by use of portable devices for this purpose or by yard-type coating equipment that rotates the pipe. Additional protective rings built up of five layers of glass fiber reinforcing, single wrapper width, continuously wound over the coating and saturated with hot enamel during rotation, shall be applied at intervals of approximately 5 ft. Uncoated space remaining after welding joints or making up collars shall be hand-coated and shall include coating and reinforcing equal to the maximum adjacent coating. Also, during the movement of the pipe into the casing, fine clay muck or other lubricant, approved by COMPANY'S inspector, is to be crowded or poured into the casing against the pipe.

3. Where pipe is to be installed in casing with patented casing spacers and bushings as supplied by COMPANY, above specifications shall apply for coating of pipe, but "protective rings" as called for above may be omitted. See Exhibit—— for details.

h. *Coating of Valves and Fittings:*

All valves and fittings to be buried shall be cleaned free of loose mill scale, rust, dirt, grease, moisture, or other foreign substance, and then primed with a regular coat of coal tar primer. Two coats of enamel shall then be applied in such a manner that the minimum thickness of coating is 3/32 in. This coating shall be tested with a holiday detector and all defects repaired.

i. *Preparation of the Ditch, Lowering Coated Line, and Backfilling Ditch:*

1. All brush, skids, pipe, pipe protectors, rocks, large clods, sticks, projecting rocks, and other hard objects shall be removed from the bottom of the ditch into which the coated and wrapped pipe line is to be lowered, so that the protective coating will not be punctured or abraded. An excavation shall be made beneath the pipe, at the point where it is supported by a belt, without damage to the coating. The ditch shall be made wide enough, where slack loops are lowered into the ditch, so that no coating is rubbed off on the sides. Whenever the bottom of the ditch contains projecting rocks or hard objects that might puncture the protective coating, the bottom of the ditch shall be padded with a minimum of 3 in. of backfill material free of hard objects that might damage the coating.

2. The coated and wrapped pipe line, except for slack loops, which shall be supported by wide non-abrasive canvas or leather belts, or by padded timbers in sufficient number that the pressure at the point of support will not cause puncture of the coating, shall be lowered to the smooth bottom of the ditch immediately after the coating and wrapping have been applied. Wide non-abrasive canvas or leather belts shall be used in all lowering of the pipe line. The CONTRACTOR will lower said line in such a manner as will provide, in the opinion of COMPANY'S inspector, sufficient slack in said line. The line should not be dropped or subjected to jar and impact. Slack loops, which have been supported on padded timbers (sacks partly filled with straw, sand, sawdust, or loose earth, free from all hard objects, may be used for padding), shall be lowered in the early morning or at night when the pipe is cool.

All coated and wrapped pipe, which has been supported in any manner on padded timbers or lowering-in devices, shall be subjected to a test with an electric holiday detector immediately before the pipe reaches the bottom of the ditch.

3. Whenever backfill material contains hard clods, rocks, or other hard objects that might puncture the protective coating, the backfill material (free of hard objects that will damage the coating) shall be carefully placed around and over the pipe by hand shoveling until the pipe has been covered to a depth of at least 6 in.; the remaining cover may contain rocks and hard objects, and may be backfilled into the ditch in the usual manner. Rock, wood, and vegetable matter are to be excluded from backfill adjacent to pipe.

4. Ditches shall be backfilled immediately after lowering the coated and wrapped pipe into the ditch.

j. *Operation of Holiday Detector and Electrical Test:*

1. The COMPANY will furnish a holiday detector, which shall be run over the finished coating at a distance behind the coating and wrapping machine sufficient to allow the coating materials to cool and harden, and to allow the satisfactory operation of the detector. CONTRACTOR shall furnish all labor and transportation to operate detector.

2. Pipe coating will be tested by the COMPANY for electrical resistance, after backfilling, with a direct current supply to establish a potential not exceeding three volts between soil and pipe. Coated pipe, showing average resistance of less than one megohm per sq ft, will be checked for defects with a Pearson Holiday Detector. Cost of repairing coating defects will be charged to the CONTRACTOR when the cause of such defects originates from carelessness or negligence of the CONTRACTOR. * * *

Fully Automatic Electric Powered Crude Oil Gathering Stations*

F. H. WARREN†

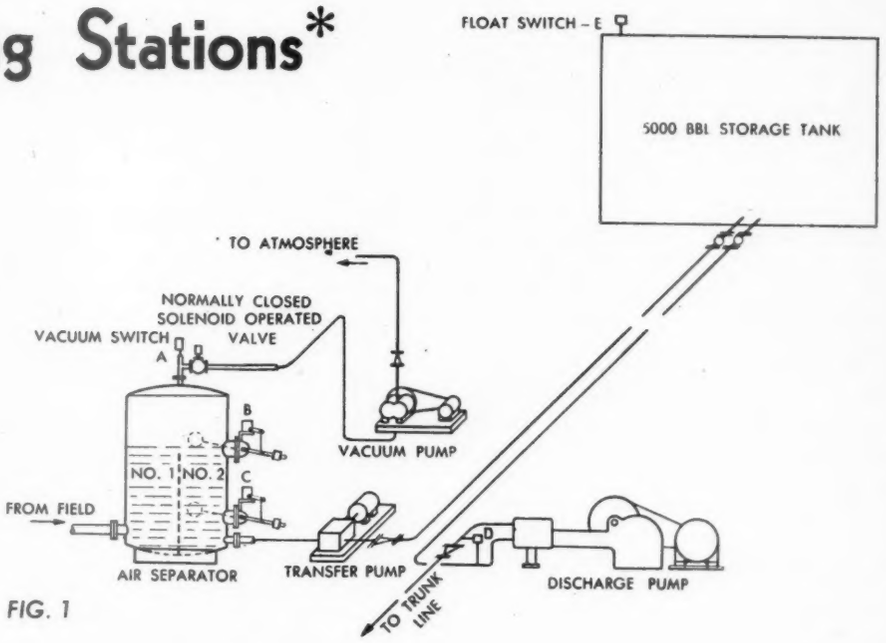


FIG. 1

In the fall of 1945, the Pipe Line Department of our company was confronted with a problem of designing a gathering system to serve an oil field, the production of which was increasing rapidly due to water flooding. Specifically, it was the old Siggins pool in Clark and Cumberland counties of southern Illinois. Originally a gathering system was constructed and a discharge line laid to a tank farm just north of the town of Casey, Illinois. Until the main trunk line of The Ohio Oil Company was completed east of Martinsville in late 1906, the crude was shipped in tank cars to the Standard Oil refinery at Whiting, Indiana. Our company constructed a pipe line to our Martinsville, Illinois, tank farm in 1906 and operated it until early in 1941 when it was taken out of service because of bad pipe and greatly reduced volume. By that time the production had dwindled to less than 100 bbl per day, and a local contractor was engaged to truck the oil to Martinsville.

Early in 1943 a water flooding project was started. By midsummer, 1945, crude production was approaching 600 bbl per day and it became evident that the old gathering system would have to be reconditioned and put back into service.

A survey revealed that the original field station was improperly situated and a new station site was selected. The old gravity system was revamped and is shown on the accompanying map. One line of the main trunk lines between Wood River and Martinsville carries Illinois Basin crude and passes within approximately 3 miles of the new station site. It was therefore decided that the oil should be injected into the Illinois Basin stream at that point. The operator of the water flood project was in the process of electrifying his operation. The power company at that time was building a transmission line into the area with ample capacity to serve us. We therefore decided to construct an electric pump station, and furthermore to make it completely automatic.

The schematic arrangement of equipment used in the original automatic field station is shown in Fig. 1. A photograph of an installation is shown in Fig. 2. An air separator was installed in the gravity line from the field in order to take care of those cases when air is accidentally drawn into the lines. The separator tank is 5 ft in diam and 7 ft high, having a partition plate extending approximately 4½ ft up from the bottom dividing the separator into two oil-tight compartments. A small Roots-Connersville blower driven by a 3-hp motor, was connected to the top of the air separator to pull out any air that might accumulate. A rotary transfer pump of approximately 200 bbl per hr capacity driven by a 5-hp motor was installed to pump the oil from the air separator to a 5000-bbl storage tank. A 4 by 6 pump driven by a 20-hp motor became the discharge pump. On the more recent installations, a sump has been added with a small capacity, float-controlled sump pump. In case of excessive leakage, such as a blown gasket, the sump will fill up and cause a second float to shut down the entire station. All motor controls and electrical equipment are of the open type and are installed in a vapor-tight room.

Since Casey station was to inject oil into the main trunk line, it would be necessary for the dispatcher to know the quantity of oil delivered into the system each hour. It was decided that for line dispatching purposes the output of a constant speed piston pump would be sufficiently uniform to indicate the quantity of oil pumped if some reliable means of recording the amount of time the unit operated could be devised. In order to record the operating time a remote reading pressure gauge was installed with the receiving instrument in the gauger's office at Martinsville some 7 miles distant. The electric circuit for transmitting the pressure impulses was superimposed on the company-owned telephone line that parallels the pipe line at this point. The receiving instrument at Martinsville records the pressure on a continuous chart. The Martinsville gauger has merely to note the amount of time Casey operated the previous hour, convert it to barrels pumped, and report it to the dispatcher hourly when he turns in his own check.

The principal difference between the automatic field station described and the ordinary field installation lies in the air separator tank. A vacuum of approximately 8 in. of mercury is maintained in the top of the air separator tank at all times, unless the tank is filled with oil to a level where the switch actuated by float B has shut down the vacuum pump. The vacuum pump is controlled by vacuum switch

*Presented before the Petroleum Mechanical Engineering Conference of The American Society of Mechanical Engineers, Amarillo, Texas, October 3-6, 1948.

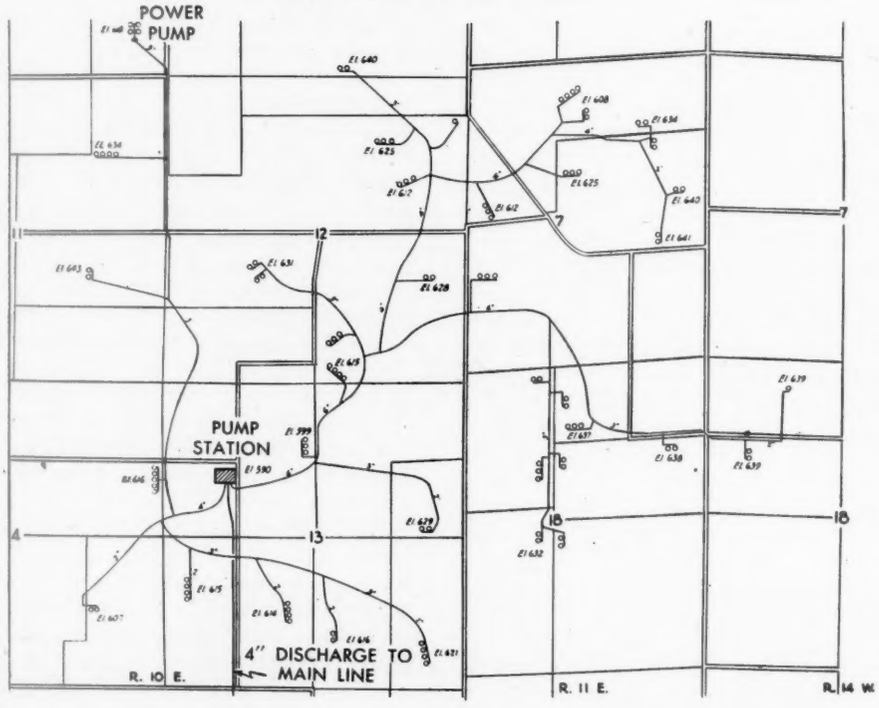
†General Superintendent, Eastern Division, The Ohio Oil Company, Pipe Line Department, Findlay, Ohio.

A, and a mercoid tube switch actuated by float B connected in series with the motor starter control circuit. The vacuum in the air separator must be below the value at which switch A closes, and float B must be in its lower position before the vacuum pump motor will start. The vacuum pump motor will shut down, however, when either the vacuum or the liquid level has been established.

In operation, the field gauger turns lease tanks on in the usual manner, and there being a vacuum in the air separator, oil from the field flows into the separator, over the partition plate, and fills compartment No. 2 containing two floats, B and C, which actuate switches having multiple mercoid tubes. When compartment No. 2 has filled to approximately the height of the partition plate, float B starts the transfer pump. If the vacuum pump was running at this time float B also simultaneously shuts down the vacuum pump. Unless air has entered the gravity lines, the liquid level in the air separator will generally continue to rise, and in the case of lease tanks elevated considerably above the station, the oil will completely fill the separator tank. In order to prevent oil going over through the vacuum pump, a normally closed solenoid operated valve is installed in the vacuum line. The solenoid of this valve is connected in parallel with the vacuum pump motor and remains open only while the vacuum pump is operating. The transfer pump continues to operate

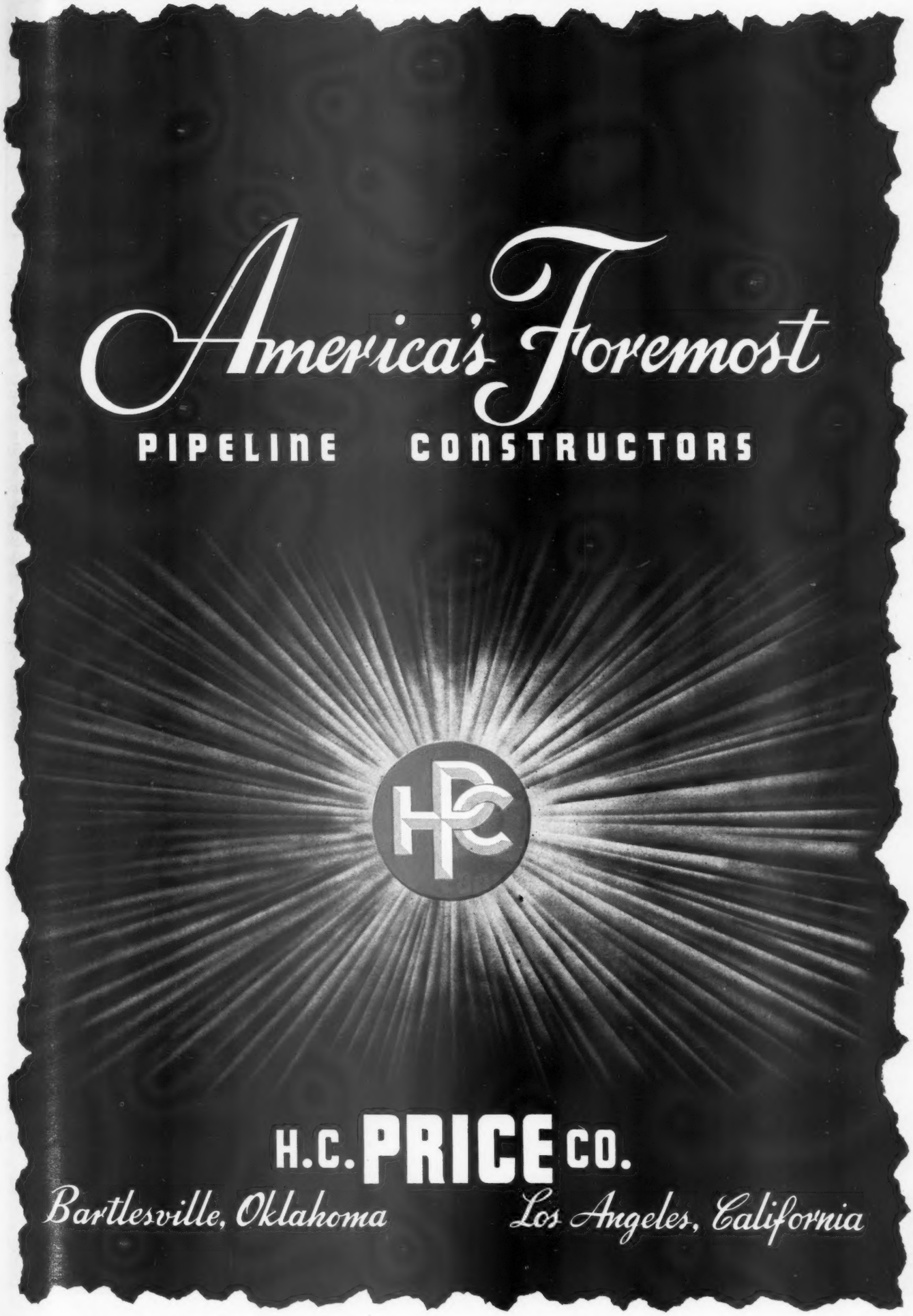
FIG. 2

Siggins pool gathering system.



until the oil in compartment 2 drops below the center line of float C, which breaks the holding coil circuit of the transfer pump motor starter and shuts the transfer pump down. Float C will not start the transfer pump; it merely maintains the holding coil circuit after switch actuated by float B has completed the circuit. A check valve is installed on the discharge side of the transfer pump.

After the oil level has reached a predetermined height in the 5000-bbl storage tank, float switch E causes the discharge pump to start. A normally open solenoid bypass valve D is installed between the discharge pump and a check valve. This solenoid bypass valve is connected in parallel with the discharge pump and performs two functions. It opens the instant the discharge pump shuts down, allowing the pressure in the pump to drop quickly and thus inform the gauger at Martinsville that Casey station has gone down. When the discharge pump starts up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valve D remains open until the motor has attained full speed. This is accomplished by means of a time delay relay. The discharge pump is driven by a normal torque, normal starting current squirrel cage motor. The unit comes on the line without difficulty against pressures in excess of 500 psi.

The automatic stations are under the direct care of the field gauger in charge of the district. He gauges the storage tank every week day at 7 a.m. and telephones the gauge into the office. He changes a recording pressure gauge chart, inspects the equipment and keeps the station presentable. Our electrical department checks the equipment about every two months to make any necessary adjustments. Availability has been virtually 100 per cent.

The first automatic electric field station went into operation in December, 1945. Production handled by this station has increased from approximately 600 bbl to more than 2000 bbl per day. The original 20-hp motor has been replaced by a 30-hp motor and the pump speeded up from about 70 bbl per hr to approximately 140 bbl per hr. A 10-in. stroke pump is on order to replace the original pump. An additional transfer pump to be started and stopped from float B will soon be installed to take care of peak loads but no other changes are indicated. We now have six completely automatic stations in operation and two semi-automatic installations, using only a portion of the original set-up.

When the engineering department first proposed this system, there was considerable doubt in our minds as to the advisability of maintaining a vacuum in the air separator. In actual practice, however, we find the vacuum pump operates only a few seconds when oil is first turned on and will seldom average more than 10 or 15 minutes operation per day. Automatic shut-off valves were installed at approximately one-third of the tank batteries and have proved to be quite an effective means of keeping air out of gravity lines. We feel some automatic shut-off valves are required for best results with this type of installation.

The automatic electric stations have been much more economical than the older type of station, utilizing engine driven pumps. In most cases the power cost has been less than the cost of fuel, lubrication, and repairs of engine driven pumps. There has been a slight reduction in manpower. The district gauger's job has been made easier because oil comes out of the lease tanks much faster. Evaporation loss has been reduced considerably. The first cost of the stations is quite reasonable and maintenance expense has been very low.

* * *

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A Case History of Some Pressure Surges*

C. B. LESTER†

THIS paper presents some interesting facts regarding pressure surges on a section of a 240-mile, 12-in. crude oil pipe line between Stoy, Illinois, and Lima, Ohio. The following description of some of the general operating conditions should enable the reader to understand the factors associated with the analysis of the surge problem. The main pump stations are largely diesel engine driven centrifugal pump units and the alternate stations or booster stations are largely electric driven centrifugal pumping units. The entire line operates as a closed system; however, the line is paralleled by a 6-in. pipe line using reciprocating pumps and operating as an open system with tankage at each station. This tankage can be used in an emergency for the 12-in. line and also for purposes of "pressure relief" from the 12-in. line.

This paper is particularly concerned with the first section of the line between Stoy pump station and Coal City, a section about 46.5 miles long. The line is telescoped from 45.55-lb pipe to 39.89-lb pipe, and has a 12-in. loop, a little over three miles long, at the Stoy end. The geographical location of this section of the line, showing the location of the different weights of pipe, is shown on Fig. 1, together with the operating conditions for both stations. When this line was first built, the Illinois oil fields were approaching their maximum flush production, and the line was so urgently needed that it was placed in service without the customary water test. After operating satisfactorily for a short time, several joints of pipe ruptured at various pressures, and it was then decided that it would be necessary to water test the entire line. The oil fill was displaced with water, the line tested to 1250 psi, and then placed back in regular operating service. After operating for nearly a year, failures were experienced coincident with electric power failures at the booster stations, which caused an instantaneous shut down at these stations. This type of failure caused an immediate increase in the hydraulic gradient over a substantial portion of the line, and pressure surges of the water-hammer variety were naturally suspected. In view of the recurrence of the trouble, it was evident that a study should be made and steps taken to prevent similar failures in the future. The following is a report and an analysis of the character of long line pressure surges and the measures taken to alleviate them.

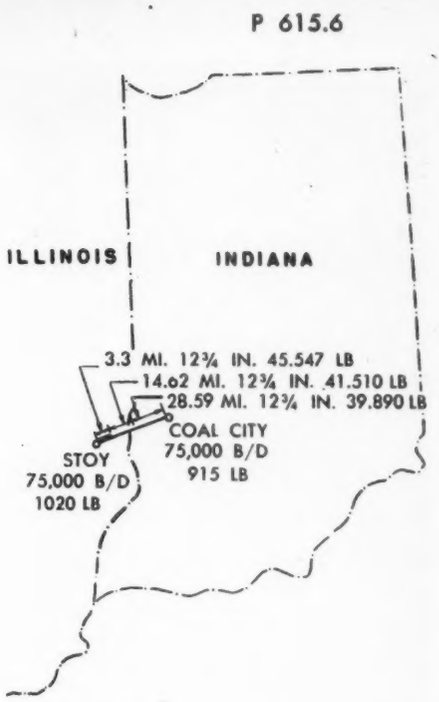


FIG. 1. Geographical location and data on Stoy-Coal City section.

Theory, Bench Scale Work

First, a study was made of all available literature concerning water-hammer. It was quite surprising to find that nearly all published data were either the results of bench scale tests, or results of tests run on relatively large diameter conduits, such as penstocks, aquaducts, etc. There was some work of interest to plumbers and building architects, perhaps, on elimination of water-hammer in building piping, but nothing in the way of practical information that would be of any use to a pipe line operator.

The theory of water-hammer is familiar to anyone who has had work in hydrodynamics; the velocity of a stream of liquid is changed by some interruption to flow, and the kinetic energy represented by the change in velocity of the fluid column is dissipated in compressing the fluid and stretching the walls of the carrier pipe.

The theory was developed thoroughly and published by a Russian, Professor Joukovsky, in 1898, and workable condensations of his findings are now standard in most hydraulic texts. The basic equation is:

$$\frac{wALv^2}{2_g} = \frac{(wh)^2AL}{2E_o} + \frac{(wh)^2LAD}{2tE_p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The first term represents the kinetic energy of the liquid column due to a velocity "v," the second term is the work required to compress a fluid with a bulk modulus "E_o," and the third term is the work required to stretch the walls of a pipe made of a material with a modulus "E_p." This equation can be solved for "h," the rise in head at the point of interruption to flow, to give:

$$h = \frac{12v}{g\sqrt{\frac{w}{g}\left(\frac{1}{E_o} + \frac{D}{E_p t}\right)}} \quad (2)$$

with moduli expressed in psi.

Formula (2) can be more easily visualized if rearranged as:

$$P_o = \frac{v_o wa}{144g} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Where:

P_o = value of the surge pressure at the point of interruption, psi.

w = density of the liquid, lb per cu ft.

a = velocity of the surge wave front, fps.

v_o = change in velocity of flow, fps.

g = gravitational constant.

The change in velocity can be calculated by:

$$Q = Av \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The velocity of the pressure wave front, equal to the speed of sound in the line, can be calculated by:

$$a = \sqrt{\frac{E_o g}{w\left(H\frac{E_o D}{E_p t}\right)}} \quad . \quad . \quad . \quad (5)$$

This "simplification" is merely a rearrangement of equation (2), but is more easily used. This entire derivation was copied almost directly from the 1927 edition of *Hydraulics* by W. H. King and C. O. Wisler.

Bench scale experiments were set

*Presented before the Petroleum Mechanical Engineering Conference of The American Society of Mechanical Engineers, Amarillo, Texas, October 3-8, 1948.

†Sohio Pipe Line Company.

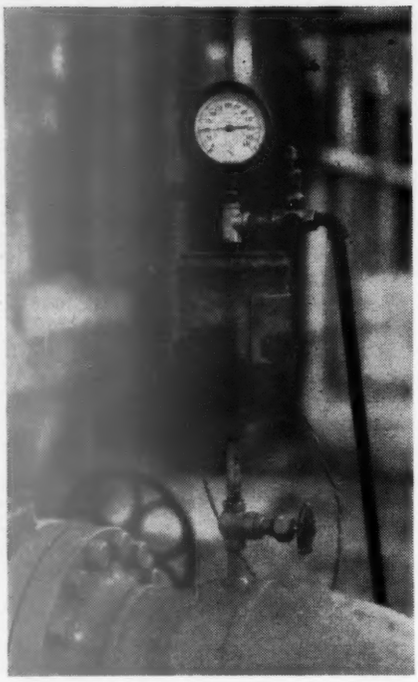


FIG. 2. Recorders.

up to develop instruments for field use and to ascertain whether controlled bench scale tests would confirm the foregoing formulae. Special electric and electronic instruments were used to insure accuracy, and it was found that for short sections of pipe with relatively large L/D ratios, the theory checked excellently with bench scale experimental data.

Arrangements were then made to set tested Bourdon tube pressure gauges on the suction side of Coal City station, and readings of the rise in suction pressure due to changes in line flow caused by instantaneous shutting down of individual pump units were plotted. Fair correlation with theory was obtained, and a report was made, recommending further work.

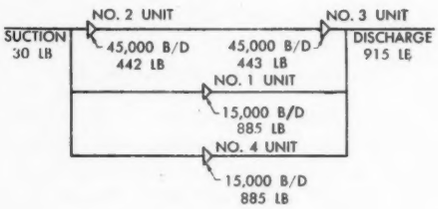
Field Tests

Even though this line was operating at maximum capacity under wartime conditions, authority was given to perform any necessary experiments on the line itself to obtain whatever information was required to eliminate interruptions to service due to pressure surge induced ruptures.

First, pressure taps were put on the Stoy-Coal City section at distances of 3.06, 7.65, 15.00, and 27.00 miles from the suction of Coal City station, corresponding to a more or less logarithmic spacing.

Our laboratory experiments indicated that pressure surges, at least on bench scale lines, had very sharp wave fronts. Also, in the experiment at Coal City previously mentioned, it was noted that Bourdon tube gauges, which, of necessity, have a high element inertia, tended to overshoot very badly; whether this was due to actual overshooting of the gauge itself, or to the passage of a sharp-crested wave front, was not known.

Based on the above observations, it was decided that some sort of instrument with essentially no inertia should be used to ascertain whether there actually was a sharp wave front on the pressure surges induced in the pipe when pump units at a station were shut down. For a pressure element, a Baldwin-Southwark SR-4 strain gauge was cemented directly to the pipe wall. For an indicator, the output of the strain gauge bridge was fed into a Brush direct-inking oscillograph. As the bridge was fed with 60-cycles a. c., it was felt that any surge crests in the order of 0.01 sec or less would be faithfully indicated.



Total capacity 75,000 B/D —915 psi.

FIG. 3. Pump operating conditions.

FIG. 4. Schedule of operations for shutting down units at Coal City

Saturday, November 4, 1944
Sunday, November 5, 1944
Monday, November 6, 1944

Operation	Time
1. Shut down No. 4 Unit	9:00 a.m.
2. Restart No. 4 Unit	9.30 a.m.
3. Shut down No. 4 Unit	9:45 a.m.
4. Shut down No. 1 Unit	10:15 a.m.
5. Restart No. 1 Unit	10:45 a.m.
6. Shut down No. 1 Unit	11:00 a.m.
7. Shut down No. 2 and No. 3 Units together	11:30 a.m.

To eliminate the human element as much as possible, strain gauges were used at the other pressure taps feeding into a Foxboro SR-4 strain gauge recorder. This instrument has a chart speed of 1 rpm per 24 min, 60 times faster than a standard pressure recorder, and the instrument movement is very powerful and positions quite rapidly.

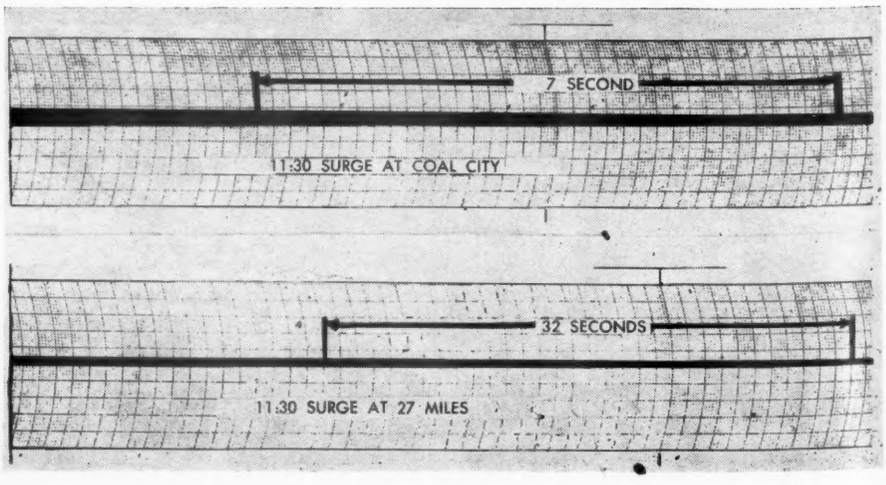
The construction of the pressure element used with the Foxboro recorders is shown on Fig. 2. A tank was made from 6⅝-in. by 0.188-in. Grade B line pipe with 1½-in. end plates welded in. Calibration curves were run on these tanks, which indicated that a straight line calibration curve could be obtained, and that there was little, or no, hysteresis present; any hysteresis that might have been present was eliminated by bleeding the pressure from the tank and "zeroing in" the units before each test run.

The pump layout at Coal City station is shown on Fig. 3, together with normal operating conditions for each pump. These pumps were shut down in a set schedule designed to give certain abrupt changes in flow, thus inducing surges in the line for test purposes. This schedule of operations at Coal City is detailed in the table of Fig. 4. Please note that the entire station was never shut down all at once: we were afraid of rupturing the line if this was done.

The entire squence of operations as outlined was followed on November 4, 5, and 6, of 1944. The Foxboro recorders, Brush oscillograph, and associated equipment were moved each day so that all but the oscillograph were set up at each pressure tap at least once.

The amount of data taken was so

FIG. 5. Two oscillograms of surges.



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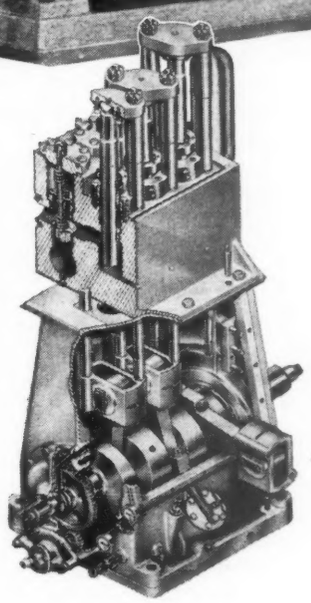

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large that it would be much too lengthy to detail here. The following interpretations of the data are significant, and are recaps of more voluminous experimental data sheets.

In Fig. 5 are shown two oscillograms of the 11:30 a.m. surge at the suction side of Coal City and at the 27.00 mile pressure tap. Two pertinent facts can be taken from these two oscillograms:

1. The type of surges induced in a pipe line by the pumping units at a station being shut down does not have a sharp crested wave front, or, at least there are no peaks so sharp that they cannot be faithfully followed by Bourdon tube gauges.

2. There is a severe damping effect on the pressure surge as it travels back up the line against the normal direction of stream flow. Note that the 11:30 a.m. surge reached its maximum, or near maximum, in 7 sec at Coal City suction, whereas the surge magnitude was reduced and the total rise took some 32 sec at the 27-mile point.

This was the first noted variance with water-hammer theory. Theory makes no allowance for frictional damping of the surge, but states that the interface travels back up the line undiminished until it reaches a point of relief, at which point a rarefication begins travelling back down the line, relieving to normal or below normal pressure, until it reaches the point of disturbance where the original pressure surge started. A second surge is induced, and the entire cycle repeats itself until the kinetic energy of the fluid column that induced the original surge is dissipated at both ends of the line and finally dies away.

Our experiments indicate that in pipe lines used in the oil industry, which have such a large L/D ratio, molecular friction in the oil and in the pipe wall absorb energy from the surge so that it continually decreases in a set, predetermined manner.

To ascertain whether the rate of pressure decrease was logical and calculable, Fig. 6 was plotted. Note that on semi-log paper, with pressure on the log scale, the plot of surge pressure vs. distance is a straight line with a negative slope, indicating that the reduction in pressure with distance is a simple exponential function. This statement is borne out by later experiments, which are to be described.

Insofar as the value of the surge is concerned, qualitative correlation with water-hammer theory is very good. Fig. 7 is a plot of surge pressure vs. change in throughput, and is, in all three instances, a straight line.

The quantitative correlation, however, is so poor as to be almost negligible. For instance, on the night of November 3, 1944, while equipment was being set up at Coal City, the entire station was shut down by a power failure, resulting in a 315-psi surge, and a reduction in throughput of 53,000 bbl per day as indicated by the flowmeter. Straight line extension of the plot in Fig. 7 closely predicts this rise in pressure; however, using the theoretical method outlined previously, taking into account all conditions bearing on the problem, and assuming E_o for crude oil as 258,000 psi, a pressure rise of only 198 psi should be expected. This is a difference of some 35 per cent.

One possible explanation is as follows. All units at Coal City are centrifugal pumps, and, as these pumps slow down, there is a drop in station discharge pressure. Although the station is equipped with check valves, it might be possible that some of this pressure bleeds backward through the pumps to the station suction if the pumps slow down faster than a rarefication can be established on the discharge side. This is controversial, but could be true. We might also be using a low value for the bulk modulus, but the 258,000 psi figure used would have to be considerably low to influence the answer to any great degree.

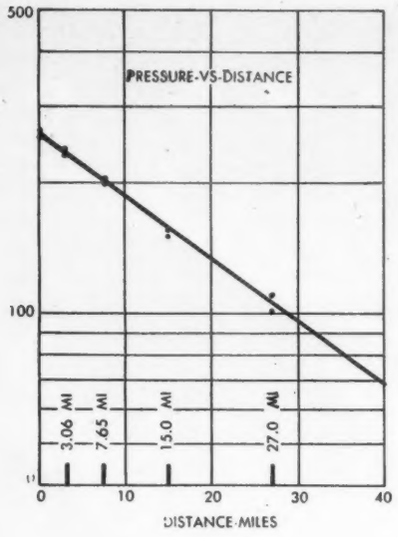


FIG. 6.

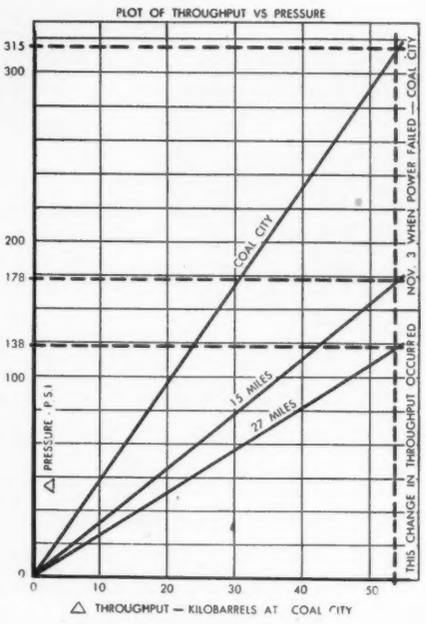


FIG. 7.

It was now known that pressure surges, over and above the rise in gradient normally expected, were present in the line when sudden variations in flow were experienced. As the usual, proved way of elimination of surges is to use surge chambers, or surge tanks, it was decided to try floating a tank on the suction of Coal City station. A 10,000-bbl tank, used with the open system 6-in. line, was available at this station, and necessary manifold changes were made to float this tank on the 12-in. station suction. The head available from the tank was not sufficient to fill pumps No. 1 and No. 4, however, which require a very high mpsh to fill properly, and the experiment was abandoned as unsuccessful. The solution, even if workable, would not have been too satisfactory, for it would have meant reverting from a closed to an open system, automatically incurring the inherent stock losses and inefficiencies of such a system.

During this time, another rupture had occurred in another section of the line, again behind an electric driven station, and immediately after the units had been shut down by a power failure.

Although we had no similar installations in our own operations, and no knowledge of similar installations in use by other operators, orders were placed for large relief valves for the suction side of Coal City station and the other above-mentioned station. These valves were specified to handle 65,000 bbl per day when set at 80 psi, without exceeding 100 psi at the inlet.

It was now known that smaller surges would damp out very rapidly, and so a set pressure was selected that would allow some variation in suction pressure, but would still hold surges to a 70-psi maximum. By limiting surge pressures to a small value, it was believed possible to not only prevent large surges from travelling back up the line for any distance, but also to eliminate shock loading of the low pressure pipe near the suction of the station. Although no ruptures had

been experienced in the low pressure end of this line, it was felt that as the pipe aged and was weakened by corrosion, shock loading of the pipe would be troublesome.

While waiting for these valves to be delivered, three spring driven pressure recorders with 7-day clocks were installed at the 3.06 and 7.65 mile pressure taps and at the end of the loop, approximately 43 miles from Coal City suction. The charts from these recorders, within the limits of accuracy of the instruments, gave a good record of the maximum value of surges produced when Coal City was shut down accidentally at various times over a 4-month period. Pressures as high as 1160 psi were found at the 43-mile tap, even though the discharge pressure at Stoy station never rose above 1040 psi; this was because automatic controllers at Stoy station took the station off stream automatically at this pressure. The data taken were plotted and generally fell in a straight line — 5° of the line shown on Fig. 6.

Relief Valves

The first relief valve was installed at Coal City station. It was mounted vertically on an 8-in. gate valve and nipple welded directly on the 12-in. station suction line, about 50 ft from the station manifold. The relief line was run into the line used in the previous experiment when it was attempted to float the 10,000-bbl tank on the station suction.

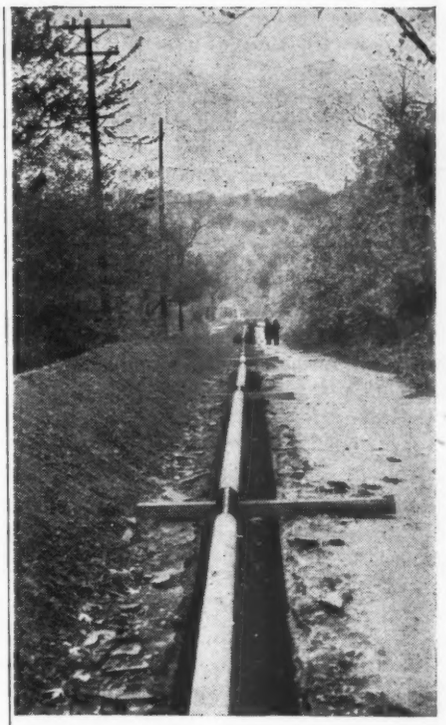
When this valve was ready for testing, all stations along the line were notified to stand by their controls, and No. 1 pump unit was shut down. The station suction rose to about 75 psi, but the valve did not blow, and so the No. 4 unit was shut down. The valve then blew wide open, oscillating wildly, and vibrated the station manifold piping some 50 ft away. The entire valve assembly, weighing approximately 1700 lb, oscillated with a frequency of about 2-3 cps, and a vertical amplitude of about 0.5 in. This vibration was so bad that the backfill was cracked over the 12-in. suction line mounting the gate and relief valves. This procedure was tried three more times, during one of which operations, No. 1 and No. 4 units were shut down simultaneously, with the same results. The vibration was very bad, but it was felt that the manifold piping was strong enough to withstand it for short periods at least, and special instructions for operating it were posted. The valve manufacturer was informed of the problem and asked to supply any information that they could which would eliminate this vibration trouble.

It was known that all the requirements of simple harmonic motion were met in a relief valve installation if certain conditions pertaining to relieving capacity, relief line friction, and valve mechanical construction were met. The manufacturer recommended that a dash pot damping mechanism be installed on the valve mechanism to limit opening and closing speeds, which, it was believed, would eliminate this vibration trouble. As this construction would have taken some time and some design work on the part of the manufacturer, it was suggested that the resilient force could be reduced by installing the valve immediately adjacent to the tank, thus eliminating, or at least considerably lowering, the variable back pressure on the valve due to friction in the relief line.

As the Coal City valve was already installed, though not working properly, the second valve was installed at the second electric booster station previously mentioned, with the outlet line from the relief valve connected directly to the tank through approximately 30 ft of 8-in. pipe. The inlet line to the valve was some 250 ft long. This valve was tested by shutting down a 20,000 bbl per day unit at the station, and the valve vibrations experienced were as bad, if not worse, than the vibrations set up by the Coal City valve. The tank plate carrying the outlet connection was sprung by these vibrations and began to leak. Feeling that further vibration might eventually pull the plate off the tank, it was decided to take the relief system out of operation by closing the gate valve on the inlet, and to request further help from the manufacturer.

Two suggestions were made, both of which involved considerable waiting and shop time, design work, etc. One suggestion was that previously considered, i.e., to use a dash pot damper, the second being to use a pilot operated valve, so that the damping mechanism could be installed on the pilot. It was, therefore, necessary either to wait 6 to 8 months for delivery of equipment to effect one of the two above-mentioned possible solutions, or develop some other damping method that could be installed quickly. Mathematical analysis would not account for the extreme vibration experienced when the only resilient force present in the second installation, in addition to the valve spring, was a small variable back pressure due to friction and the entrance loss in the 30-ft length of pipe. It was seemingly evident that some other disturbing force must be present in the system.

It had been noted that the valve



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body itself, and, of course, the associated piping, depressed sharply when the valve first opened, and vibrated continuously thereafter. It seemed likely, therefore, that if the oscillatory period of the valve system was lowered below the critical point by loading the body, oscillation of the relief assembly could be eliminated.

A 4-yard concrete damping block was poured under the second valve, and, under all operation conditions, vibration was completely eliminated. A person standing 10 ft away could not hear the valve open, but could hear high velocity stream passing through it as flow was established.

The Coal City valve was then moved inside the tank dike and installed on a damping block, and this change also eliminated all vibration.

With these valves, it has been possible to retain all the advantages of operating with a closed system, and still eliminate all pressure surges of any magnitude by limiting the rise in suction pressure at these two stations.

Conclusions

The above is a case history of some experiences with long line pressure surges that has developed four interesting pieces of information that should be of use to others who might be experiencing trouble of the same nature:

1. Pressure surges are generated in a pipe line when any variation in flow occurs, the value of these surges being directly proportional to the change in throughput in accordance with predictions made from water-hammer theory.

2. Although the pressure surges induced in the pipe line by variations in flow produced by shutting down centrifugal pumps are qualitatively predicted by water-hammer theory, quantitatively the results obtained do not follow theoretical predictions at all. Variations produced by shutting down centrifugal pumping units produce surges about 35 per cent higher than those predicted by water-hammer theory. Bourdon tube gauges will overshoot rather badly, but return almost immediately to a reading that accurately indicates the maximum of the surge crest.

3. For lines with relatively large L/D ratios, the value of pressure surges diminishes with distance from the point of interruption to flow in a simple exponential manner, during which time the length of the wave crest is lengthened. No allowance for this effect is made in water-hammer theory.

4. Pressure surges can be eliminated or so reduced in amplitude as to be no longer dangerous by use of large relief valves on the suction side of the stations introducing the surges. To prevent oscillation of these valves, which have to handle essentially full line flow with low accumulation, it is necessary to damp out what would otherwise be very dangerous vibrations by installing heavy damping blocks under the valve body to lower the period of oscillation of the system to a point where full line flow can be established through the valve and relief line before oscillation begins.

The use of relief valves represented a solution to one particular pipe line pressure surge problem. These installations could not have been made economically if tankage had not been available at the stations involved.

Pressure surges are only one of the possible effects that produce stresses in pipe lines over and above the normal stresses caused by the internal working pressure. This study of pressure surges had lead to the study of other stresses not normally considered in design calculations, such as residual or "locked up" stresses in the pipe itself, and stress corrosion. We are continuing work on the study of these stresses, though movement of this work has not progressed far enough to justify attempting to formulate conclusive answers. ★★★

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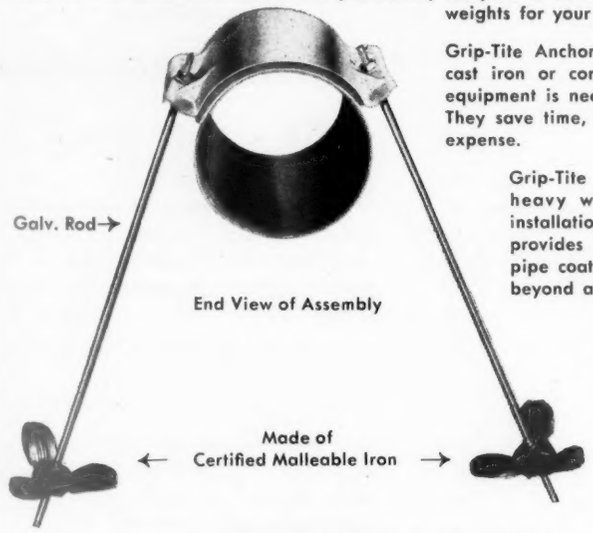

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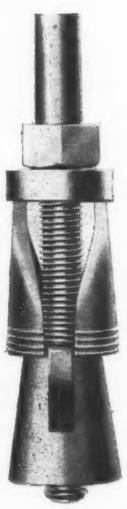

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Lease Tank Settings, Connections, Operations*

J. C. STIRLING†

APPROXIMATELY 34,000 pipe line runs are made daily in the United States, where the custody of oil passes from producers and royalty owners to the purchasers and transporters. Even though these transactions ring up oil sales totaling $15,000,000 daily, there is probably less consideration given to the economics of lease tank battery design, installation, and operation than to any other single item of the oil industry.

Because lease tanks and batteries frequently are improperly arranged and equipped to permit correct and safe handling of oil runs by the pipe line, the importance of a uniform program for setting, connecting, operating, and maintaining lease tanks cannot be over-emphasized. In the interest of both the producer and the pipe line, careful attention should be given to locating and equipping tanks so as to insure accurate handling of production and to protect the safety of pumpers, switchers, and gagers who must work on and around the tanks under all sorts of conditions.

I do not choose to go into detail on the matter of design, connection, and operation of lease tanks, as it would to a great degree duplicate work that has already been done by various API committees. However, I do wish to bring to your attention some of the possible savings to both producing and transportation companies with the adoption of better standards and better practices.

Table 1 shows the difference in tank diameters as revealed by a survey compiled by company "A" of 511 tanks distributed throughout Oklahoma, Kansas, and Texas. The tanks were all steel, and were taken consecutively according to company numbers. No special effort was made to pick tanks of various diameters, and the table includes only a portion of diameters encountered for each nominal size.

TABLE 1

Nominal tank size, bbl.	Number of different diam.	Range of diameters, ft.
100	41	7.89 to 10.06
150	11	9.43 to 10.02
200	33	9.24 to 12.07
250	24	11.98 to 15.42
300	8	10.79 to 15.24
500	27	14.76 to 21.59

Although some API committees have previously approved and submitted a tentative code, No. 12-D, for lease tank fabrication, this code is not followed by tank manufacturers, who advise that tank sizes, as provided in *Code 12-D*, do not permit the use of standard size steel sheets as manufactured by steel mills and that, to follow the code, would result in considerable wastage. It appears, therefore, that consideration should be given to changing sizes of tanks to permit use of standard size sheets, thus reducing loss to a minimum.

No record was made of distances between tanks; however, the variances were comparable to variances in the diameters of the tanks. The importance of standardization of the center distance for the setting of lease tanks should not be overlooked either by the lease operator or transporter. Standard center distances will permit the prefabrication, installation, or re-use of tank headers furnished by the pipe line company.

As an example of the need for better standards in lease tank operation, company "B" made a survey of unsatisfactory conditions in tank batteries in the Mid-Continent, West Texas, New Mexico, and East Texas areas, and found the unsatisfactory conditions indicated in Table 2.

TABLE 2

Items needed or requiring attention	Area: Mid-Continent	West Texas-New Mexico	East Texas	Total
Darts on Merco stops	3	9	...	12
Bonnets on gas roller valves	7	17	...	24
Leaking pipe-line stop	3	8	...	11
Sample cocks on tank	10	22	1	33
Wooden plugs in shell	28	6	1	35
Seams or lower chime leak	5	23	...	28
Hoops need driving wood	...	5	...	5
Visible drain on bleeder line	11	87	6	104
Visible drain inside fire wall	3	29	4	36
Visible drain covered	6	27	55	88
Stop leak on bleeder stop	6	24	...	30
	82	257	67	406
Safety				
Clean up inside fire wall	17	74	7	98
Provide walkway to gauge hatch	66	9	68	143
Repair walkway	3	16	22	41
	86	99	97	282
Gauging practices				
Locate gauge latch over pipe-line connection	63	11	83	157
Filling and bleeder connection next to pipe-line connection	364	311	124	799
	427	322	207	956
Total number of items	595	678	371	1,644
Number of lease batteries	391	446	162	999

From these figures, we find that the initial cost of one high 500-bbl tank is approximately 75 per cent of that for two 250-bbl tanks. The same is true in comparing a high 1000-bbl tank with two 500-bbl tanks. The increased installation and piping cost brings the cost of the initial installation up to an estimated 50 per cent greater for the small tanks than for the larger tanks; thus the economics of removing a portion of the tanks after the production has declined has been largely offset in the initial installation cost.

Other reasons for the use of fewer tanks of larger capacity in a battery, in addition to lower initial cost of installation, are:

a. Less evaporation losses to both producing and pipe line companies resulting from less surface exposed to atmosphere and less time required to gravitate oil from tanks.

b. Lower connection cost on the part of the pipe-line company serving the lease, as both labor and critical materials are saved in connecting fewer and larger tanks.

c. Less gaging expense, as the same amount of time is required to gage and test the oil in a small tank as in a larger tank.

d. Improved operation of gathering systems resulting from the use of higher tanks, increasing the rate of

TABLE 3

Size, bbl.	Cost to erect 2 low tanks	Size, bbl.	Cost to erect 1 high tank
100	$ 840	200	$ 600
250	1,536	500	1,176
500	2,568	1,000	1,860

*Presented before Annual Meeting of the American Petroleum Institute, Chicago, Illinois, November 8, 1948.

†Standard Pipe Line Company, Tulsa, Okla.

gravitation from the tanks into the pipe line.

The use of overflow lines is not recommended, due to the possibility of losses and inaccuracies; however, if used, they should be equipped with lock stopcocks or plug valves with sealing devices, placed where they can be sealed closed while tank is on the line or in custody of a pipe line company. These lines, unless they are so equipped, are conducive of operations which can result in losses that may work to the detriment of either the producing or the pipe line company, depending on the conditions involved. Oral reports, which have not been confirmed, indicate that losses as much as 7000 bbl of crude oil per year have resulted in one district where equalizer lines were not equipped with lock stops. Appreciable losses to the pipe line companies have also been known to result from the use of these overflow connections, particularly where crude oil backs up into low batteries, causing a tank on the line to overflow into other tanks in the battery not then in custody of the pipe line company. Losses of oil suffered by the pipe line company have also been known to result from expansion of crude due to sun temperature where tanks have been gaged and placed on the line early in the day and held back due to higher tanks going out first. This expansion, due to increased temperature as a result of delayed exhaustion of the tank, results in crude overflowing into producers' tanks through the overflow lines unless equipped with valves and unless they are closed.

Following are other suggestions for uniform lease tank batteries:

a. Tanks should be set on a grade sufficiently solid to prevent appreciable settling. Tanks appreciably out of *level* should be leveled before pipe line connection is made.

b. *Dents* in tanks should be rounded out before pipe line or flow line connections are made.

c. Tanks should be set with pipe line connection *openings aligned* perfectly.

d. *Steps and walkways* to be properly constructed, safe, and equipped with at least one guard rail.

e. All tanks of nominal capacity in excess of 100 bbl to be equipped with two *gage hatches;* the No. 1 hatch to be directly over the pipe line connection for all tanks; the No. 2 hatch (for tanks with nominal capacity in excess of 100 bbl) to be located diametrically opposite the No. 1 hatch. The center of the gage hatches should be at least 12 in. from the shell of the tanks and placed so that no obstruction on the tank bottom shall interfere with the accuracy of gage made through the hatches.

f. The *pipe line connection* should be located directly *under the No. 1 gage hatch,* with the bottom of the outlet at least 12 in. above the tank bottom, for tanks having flat bottoms; or above the gage plate for tanks with cone bottoms.

g. *Drawoff connections* should be located on or near tank bottom diametrically opposite the No. 1 gage hatch; all drawoff connections to be equipped with lock stops or plug valves with sealing devices.

h. *Flow lines* to be located on the front of tank, away from the No. 1 gage hatch, but where the flow line valves may be operated from the walkway; possibly the flume pipe (perforated in the vapor space) should be standardized, which would direct the flow to the center of the tank; all flow lines extending below the oil height of tank to be perforated in the vapor space above the oil height; flow line drop to each tank to be provided with stop or valve.

i. *All vent lines* to be provided with lock stop or plug valve with sealing device on the drop to each tank, and should be so placed that the vent line can be sealed closed while the tank is on line.

There is a definite need for cooperation between lease operators and pipe line companies in the selection of the best sites for tank batteries. From the standpoint of economy and conservation of materials, location of tanks can result in unwise spending and waste of materials, or in substantial savings to both parties concerned. In some cases, tank batteries have been erected in a low place where the gravitation of oil by pipe line was impossible, whereas a little study by the representatives of the two companies would probably have resulted in a tank site being selected at a strategic point beneficial to both the lease operator and the pipe line. Operation and maintenance costs are reduced when gravity systems can be constructed, and better services can be rendered by gager running oil if pumping can be eliminated.

Adequate storage and treating facilities are also important factors of mutual interest to the lease operator and transporter. On many leases increased gaging service is required because of insufficient tankage, thus putting the pipe line company to additional gaging expense, involving also added expense to the producer in gaging and topping out his own tanks more frequently. The practice of treating oil in storage tanks due to lack of separate treating facilities frequently reduces the amount of net storage available. Adequate treating facilities would eliminate many refusals to run tanks of crude not meeting pipe-line specifications. This, coupled with sufficient storage, will effect savings to both the operator and pipe line company.

Many companies continuously stress safety to their operating personnel, while tolerating poor housekeeping in and around the lease battery—thus contributing to the defeat of any progress along these lines. It is a responsibility of the lease operator to establish and maintain good housekeeping on and around the lease tank battery at all times. The carrier's gager should cooperate with the producer in his efforts to maintain this condition by avoiding unnecessary oil spillage and such bad practices as leaving dirty rags or broken seals lying around inside the fire wall. The frequently encountered practice of permitting water, oil, and water and sediment to accumulate around the tanks and inside the fire wall, to the point where it prohibits the proper inspection or operation of the connections and necessitates the pumpers or switchers and pipe line gager to wade through this accumulation in order to perform their daily chores, has long been one of the sore spots of the men who must work around these tanks during all kinds of weather. Poor housekeeping constitutes a potential fire hazard at all times; and any accumulation of oil, unless properly protected from lease properties by adequate dikes (such as burn pits) may become ignited by lighting sparks from a distant fire or a carelessly dropped match or cigarette. Much more could be said on the danger of the switchers or the gager slipping or falling on the walkway leading to, as well as around, the battery, or while working on the gaging platform, if the surfaces are not maintained free of oil, water, and water and sediment. Adequate drainage away from the tanks and proper disposal of water, and water and sediment, to burn pits should be considered in the selection of the tank site, and should be continuously checked to see that proper drainage is maintained after the lease is actually in operation.

Acknowledgment

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